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A REVIEW OF RECENT METHODS AND RESULTS IN SUGAR-CANE BREEDING

A. GLENDON HILL

(*Sugar-cane Research Station, Mauritius*)

WITH PLATES 6 AND 7

Introduction.—Probably on no crop has so much time and money been spent in research in the last fifty years as on the sugar-cane. Much of this expenditure has been on factory work, so that this side of the industry has reached a very high degree of efficiency. To-day, there is a tendency to concentrate more resources on field research, particularly 'cane-breeding', with the result that every important sugar-cane country now supports its own cane-breeding station,[1] where the production of specialized canes, bred for local conditions, is undertaken. This arrangement supersedes to a large extent the older system of importing numerous varieties for trial from abroad, with all its attendant dangers of introduced diseases and insect pests.

The most notable event in the sugar-cane world in the past half century was undoubtedly the discovery of the fertility of the sugar-cane seed or fuzz. Before this discovery was made, the production of new varieties was dependent on the discovery and propagation of the occasional obvious bud 'sport' that was unintentionally produced from time to time. Although the sugar-cane produces sports quite frequently, perhaps due to mutilation at planting [1] and during frequent cropping operations, yet this method of producing new varieties is very limited in its scope, though several famous varieties of the past have been produced in this way. This discovery of the fertility of cane seed was made at an opportune time, and it can be said that the comparatively new science of cane-breeding, resulting in the production of healthy new seedling varieties, has since then saved the sugar-cane industry in certain countries from the disaster that threatened through the destruction by diseases of the old-established varieties and competition from beet-sugar [2].

To-day, at least a dozen cane-breeding stations are established throughout the sugar-growing countries of the tropics, and in this review an attempt is made to summarize the more recent methods and results of some of these establishments. It is regrettable from the scientific standpoint, that, owing to unfortunate experiences in the past, the results of certain cane-breeders are no longer published for general circulation and that the varieties they produce may no longer be distributed to other countries, lest they too should benefit.

Nature of breeding-material.—Although a strictly practical science, very little genetical research has been done by cane-breeders, as, owing to the hybrid nature of the sugar-cane, Mendelian laws are not immediately applicable to the material in hand, so that the cane-breeder knows no such thing as the 'pure lines' beloved by other plant-breeders. For

[1] Exceptions are South Africa and Formosa, which are unsuitable, climatically, for cane-breeding.

this reason cane-breeders have concentrated on the production, by various means, of large hybrid populations, from which to select seedlings exhibiting marked hybrid vigour, combined, of course, with the necessary qualitative characters and acceptable form. The cane-breeder, having found the rare seedling of outstanding merit from amongst the large hybrid populations bred annually, is in the happy position of being able to fix and propagate it vegetatively at once as a clonal variety. This advantage, however, is more than counterbalanced by the difficulties experienced in subsequent field-testing operations to be mentioned later.

Past successes.—Cane-breeding has now been proceeding steadily for many years, notably in British India, the British West Indies, Java, Hawaii, and Mauritius, so that numerous outstanding seedling varieties have been produced. Some of the most famous in recent times are POJ. 2878, H. 109, BH. 10 (12), D. 1135, and CO. 205, all of which surpassed the old-established varieties in the particular countries in which they were bred, and some of which have also become famous elsewhere. Few botanical discoveries of recent years have excited so much interest as did the production of the variety POJ. 2878 by the Dutch breeders in Java in 1921. This remarkable variety, like several other successful modern seedling varieties, is a polyploid form, resulting from the 'nobilizing' of the wild sugar-cane, *Saccharum spontaneum*, being a 3rd-nobilized form of this wild cane. As there is no reason for supposing that *S. spontaneum* is the only wild *saccharum* form suitable for nobilizing, cane-breeders, in the search for hybrid vigour and disease-resistance, are now hybridizing noble canes with other wild *saccharum* species, such as *S. robustum*, *S. ravennae*, and *S. munja*. Of these forms, the first two would appear to be more promising than the last-named, which produces seedlings of poor stem-growth. *S. narenga* has also been used in India but was given up as being unpromising [3]. Apart from interspecific crosses, intergeneric crosses have also been made of late years between the noble cane *S. officinarum* and *Andropogon sorghum*, but so far breeding-work has not proceeded beyond the F_1 generation owing to the sterility of these hybrids [3].

If one might be allowed to criticize the very successful Dutch work done in Java on interspecific crossing or nobilizing, it would be in regard to the pedigree [4] given to such famous forms as POJ. 2878, POJ. 2883, POJ. 2722, and POJ. 2725, which is entirely empirical, it being assumed from morphological and cytological observations that Kassoer, one of the ancestors of the above canes, is a natural 1st-nobilized form of *S. spontaneum* crossed with Black Cheribon. In support of this criticism, it may be pointed out that artificial Kassoer, produced by crossing noble canes with *S. spontaneum*, differs appreciably from natural Kassoer, the wild ancestor of POJ. 2878. However, this criticism is not of great importance to the cane-breeder, as the production of superior seedling varieties depends not so much on theoretical considerations as on the discovery of the best parent types by practical breeding-work.

Choice of parent types.—Our almost complete lack of accurate knowledge regarding inheritance in the cane makes the choice of parents for breeding purposes largely a matter of long study and experience. In

judging what constitutes the best parent types, it would seem that those prolific combinations producing the greatest extremes of variation amongst their seedlings are more promising than those yielding a high proportion of good, but not outstandingly good, seedlings. Parents yielding seedlings of high polyploid form are promising in this connexion.

It is unfortunate that in cane-breeding the results of one year cannot always be reproduced in the next, as a variety proved to be an excellent parent in one year may fail to flower again for some years for unknown reasons, or a male-sterile variety, normally used as a 'female variety', may suddenly produce a certain amount of pollen and turn 'male'. These variations, although very trying to the breeder at times, can be exploited, however, by close observation and by treating each inflorescence used for crossing on its merits. In late years much painstaking work has been done in this connexion, particularly in regard to time and duration of pollen-shedding in certain varieties [5].

Crossing technique.—The technique of crossing in cane-breeding has not altered appreciably in recent years except in regard to the spread of the open-crossing method, combined with the SO_2-method for preserving 'male' or 'female' inflorescences during crossing. Cross-fertilization by the first method is usually carried out by placing several 'male' inflorescences or arrows around the so-called 'female' arrow, which is chosen because of the suppression of its pollen-producing powers, emasculation being out of the question owing to the labour involved. Selfings are of course occasionally produced when using this method, as few female varieties are completely, or constantly, male-sterile, but these selfings, it is believed, are eliminated later owing to their poor growth. This method of cross-fertilizing may be carried out by the 'open' method, when the only protection from foreign pollen is the circle of surrounding male arrows; or the cross may be protected by one of several methods, such as the Lantern method, devised in Barbados. The spread of the open-crossing method in recent years is largely due to the realization by breeders that it is of little use taking special pains, other than isolation, to eliminate foreign wind-borne pollen by bagging or other means, when there is the ever-present possibility of the so-called female arrow producing a certain amount of pollen resulting in selfs. Certain varieties used in breeding have been found to vary in the extent of their male-sterility, as between the beginning and end of a flowering-season, as well as from year to year, as mentioned above. For this reason it is sometimes possible, by close observation and periodic pollen tests, to use a normal male variety as a female during a short period, when for some unknown cause its male characters are suppressed. The factors influencing the time and degree of flowering and the degree of male and female fertility in the sugar-cane are as yet little understood, but experiments are now in progress that attempt to control these factors, (*a*) by varying the time of planting after the method of Schaffner, who obtained complete control over the flowering of maize, and (*b*) by applying different manurial treatments, such as lime, phosphate, nitrate, no nitrate, &c., all of which are said to influence fertility in other plants [6]. Could even a certain measure of control over flowering be obtained, it would be of tremendous

value to the cane-breeder, who is hampered not only by irregular flowering but also by the non-flowering nature of certain famous standard varieties, thus making the breeding of daughter types a very difficult problem. In spite of extensive experiments conducted during recent years, no thoroughly practical method has yet been developed for preserving cane-pollen in a viable condition for any appreciable length of time, so that differences in time of flowering between male and female varieties are difficult to overcome. The most satisfactory method so far discovered for overcoming these differences in flowering periods is that used in Java, where by establishing male-variety plots in the mountains the early-flowering male varieties are retarded, thus making it possible to cross them in the lowlands with female varieties flowering at the normal period. For this purpose the male inflorescences are cut and transported daily by car to the lowlands. The converse arrangement could also be carried out, presumably provided that the mountain climate was suitable for seed-setting.

The isolating and preserving of inflorescences during crossing has received much attention in recent years, the two methods most commonly practised to-day being *marcottage* and the so-called SO_2-method of Hawaii [7]. In the first, which is much used in India, large numbers of male and female canes are rooted some time before the flowering season, so that when flowering begins the canes can be severed, transported to a protected place, and the crosses made by bringing the appropriate ♂ and ♀ canes together, each being rooted in its separate pot or container. In Hawaii the SO_2-method has been highly developed of late, the ♂ and ♀ inflorescences for crossing being cut with several feet of cane attached, just before the opening of the florets, and placed in vessels containing a solution of 0·01 per cent. SO_2 and 0·01 per cent. phosphoric acid. The vessels containing each cross are then isolated and left until the seed matures, the solution and the male arrows being renewed periodically, as required. The duration of flowering, and consequently the time occupied in making a cross, varies from seven to fifteen days. This SO_2-method, so successfully carried out in Hawaii, is not generally successful elsewhere, owing to the difficulty experienced in overcoming the toxic effect of the SO_2-solution, which frequently results in the death of the female inflorescence before the ripening of the seeds. The method would appear to be an unnatural one for this reason, and it has yet to be proved that the toxic effect of the solution does not adversely affect the seedlings produced. The method, however, would seem to be generally applicable for preserving ♂ arrows, as the time taken for the solution to reach the pollen-shedding flowers amounts to three or four days, whilst the ♂ arrows are often removed every few days in any case, in order to obtain large quantities of viable pollen. In Java, where successful cane-breeding has been carried on for forty years, the SO_2-method is not used, the male arrows, kept in water only, being renewed daily during the duration of a cross, which is always carried out by the open method. Again the female arrows consist of normal inflorescences attached to the parent plant in the field, so that the whole crossing process as carried out in Java is a simple and natural one.

Seedling technique.—The technique used for raising cane-seedlings varies considerably in detail throughout the cane-breeding countries of the world. The usual procedure is to plant the delicate and short-lived seed in shallow boxes, shortly after ripening, transplanting only the most vigorous seedlings into pots when four or more inches high, where they are allowed to establish themselves, finally transplanting the best of these into the field. There would appear to be some doubt as to the soundness of this method of selecting seedlings at very early stages, i.e. potting only the most vigorous from the box-stage and only transplanting the best from the pots to the field. Bregger, of Porto Rico, in a paper [8] presented in 1932 dealing with seedlings transplanted directly into nursery beds, instead of pots as is usually done, concludes 'that selection on the basis of vigour in the early stages of the first year is not desirable'. This work in Porto Rico, it should be noted, was carried out with seedlings containing both noble and wild blood. In Barbados, on the other hand, working with seedlings of noble blood, a significant difference has been established between the final performance of the best seedlings, selected by observation at the pot-stage, and the final performance of the unselected seedlings from the same batch, indicating that it is safe to begin selection work at the pot-stage when dealing with seedlings of noble canes or *S. officinarum* [9]. In the case of seedlings containing wild blood, it is quite possible that early vigour is not maintained and that the less wild and more desirable hybrids in the batch are retarded, so that selection at the pot-stage in that case may be unsound. This question needs, and is receiving, careful investigation, particularly in regard to the selection of seedlings in their very young stages, i.e. when still in the seed-boxes.

Field-trial problems.—Of all the operations involved in cane-breeding, perhaps the most difficult is that of testing the progeny in the field. The difficulties are caused chiefly by (*a*) the necessity for testing the ratooning powers of the new varieties, as in most sugar-growing countries several ratoon crops are raised after the original plant-cane or virgin crop; (*b*) the small quantity of planting-material available for the 1st-yield trial; (*c*) the interaction between the new varieties due to varying height and vigour, and (*d*) the time taken to raise a crop, which varies from 12 to 24 months according to climate. As 5 or 6 ratoon crops are commonly taken in some cane-growing countries, this means that theoretically 8 to 16 years would elapse from the time of breeding a new variety to the time of its distribution, after testing it through 1 plant and 5 ratoon crops. Actually, in practice, varieties are usually released for preliminary trial on sugar estates long before this time, as few experimental stations could afford to carry out such prolonged trials in the case of every promising variety produced.

As stated above, two of the chief difficulties experienced in cane-testing by the ordinary modern methods of field lay-out are caused through lack of planting-material and differences in seedling-vigour, so that if, say, ten second-year seedling varieties are put into a Latin square 10 holes by 10 holes, the results are likely to be vitiated by the interaction between varieties in spite of the method of lay-out. Nor is wide spacing

a sure cure for this evil, as some varieties, if spaced too widely apart, are liable to sprout at the nodes, so that a breeder might be tempted to discard them for this apparent fault, whereas the same canes might be admirable in this respect if planted at the ordinary spacing used on sugar-cane plantations. This problem of interaction might be solved in two ways: (*a*) by multiplying the planting material, thereby losing a year, before carrying out the first-year yield-trial, which can then be laid down on a reasonably large scale with buffer rows to eliminate interaction; and (*b*) by using each node of the original plant as a single-eye cutting, it having been shown recently that, under nursery conditions, the yield from each of such cuttings equals the yield obtained from a normal top cutting, or sett, containing four or more eyes [10]. By this means 150 or more single-eye cuttings can easily be obtained from one stool, whereas the same stool in normal practice would give only ten top setts for planting. Again, the application of the comparatively recent discovery that a considerably increased percentage germination-figure is obtained by soaking setts in a saturated solution of lime for 12 hours before planting, results in a great saving of planting material [11].

As recent years have seen the adoption by all cane-breeding stations of biometrical methods and modern lay-out of field plots, it is to be expected that, as the result of accumulated experience, testing methods will be considerably improved in the future as the nature of the material in hand is better understood, especially in regard to the interaction between varieties. The investigations on roots now being carried out in Barbados and Mauritius should aid considerably in this connexion.

Tests for 'total solids'.—The recent introduction of the hand-refractometer has been of very considerable help in cane-testing, as this instrument allows samples to be taken from standing cane in the field and the 'total solids' of each sample to be quickly determined. The technique of sampling and operation has now been so perfected that it is possible to examine large populations of new hybrid seedlings standing in the field with the assurance that no seedling of outstanding richness of juice will be overlooked. The method, moreover, is a perfectly safe one, as high correlations have been obtained between total-solids-per cent. juice and sucrose-per-cent. juice, as well as between this richness in the first-year seedling and the subsequent crop planted from this first-year crop [12].

With regard to richness in the sugar-cane, until a short time ago it was generally believed that there was a definite antagonism between quantitative and qualitative characters in first-year seedling-populations, and that to select for high yield of cane was to sacrifice the necessary attribute of high sucrose-content. However, as the result of an investigation carried out during 1933, it is now known that there is no significant correlation in batches of first-year seedlings between weight-of-stool and total-solids-in-juice, so that there would appear to be no danger in selecting 1st-year seedlings for weight, following this up by tests for total solids, &c. [13].

Disease-resistance trials.—Perhaps one of the most noticeable of recent advances in cane-breeding is the general adoption of methods for testing disease-resistance in newly produced varieties, with the object of elimi-

nating all those that are susceptible. The successful work done by Soltwedel in Java many years ago in combating Sereh disease by raising disease-free seed-cane in the mountains is already well known [14]. The modern method most commonly used is to test all newly produced varieties very early in their history by allocating a portion of the limited planting material available to disease-resistance trials, where the young plants are interplanted with diseased canes and bombarded with such major cane diseases as Gummosis in order to determine their resistance or tolerance as soon as possible. It is fortunate that parent varieties that are themselves disease-resistant appear to transmit this quality to the majority of their seedlings.

Resistance to insect attack.—In some quarters, it is thought possible to breed for insect-resistance as well as resistance to disease. For instance, the White Grub which does considerable damage to cane roots in certain countries lives for the most part in the top 9 in. of soil. As this is the zone in which the cane normally concentrates most of its roots, it is believed that by breeding a cane type with roots concentrated in a lower zone, considerable tolerance to white-grub attack might be obtained [15]. Such plants have already been bred and are now undergoing trial. Root-studies are now realized to be of considerable importance in cane-breeding in connexion with adaptation for soil types and wind-resistance, as well as for insect-resistance, but being of a very specialized nature, they are really beyond the scope of the cane-breeder, who normally could not afford the time necessary for such prolonged and detailed studies. For this reason there is a tendency in modern cane-breeding establishments to link root-research with plant-breeding by employing plant-physiologists to study cane varieties in relation to their environment. This work is in its infancy but is of considerable promise.

Fundamental research.—The cytological investigations carried out by Bremer [16] du ing the last few years are certainly the most important contribution ever made to pure science in relation to cane-breeding. This worker has shown that certain famous cane varieties, such as POJ. 2878, are polyploid forms of high chromosome number (120 in this particular variety), and consequently it has been suggested that this character may be correlated with high yield, and that cane-breeders should, therefore, aim at breeding polyploid forms. As a consequence of this work, cane-breeders in Java have back-crossed 3rd-nobilized *S. spontaneum* with *S. spontaneum* itself and by this means have succeeded in producing hybrids with chromosome numbers as high as 170. Such hybrids, known as New Style Kassoer, must of course be further nobilized before commercial varieties can be expected.

Bremer's investigation has reached the stage of explaining certain genetic phenomena in cane-breeding, but the results are without definite application in breeding-work as yet. Cytological work is not likely to aid the breeder in the selection of better varieties, but the chance of obtaining desirable extreme types will probably be greater when polyploid forms are bred.

Apart from the above investigation, little new work is to be recorded, but one may mention the X-ray experiments [17], carried out with a

view to obtaining seminal mutations, and the experiments on inbreeding designed to produce pure lines of cane for genetical study. Neither of these lines of research has yet proceeded far enough to warrant review.

Future trends.—As to future progress, it would seem that the day of the specialized sugar-cane variety must come to stay in all cane-growing countries, and that even in those countries, such as Natal, which by climate or other conditions are unable to carry out cane-breeding, extensive seedling-selection work must be undertaken if progress is to be made in the production of better varieties. This could be done safely by importing cane seed or fuzz of chosen combinations from the best-equipped establishments abroad, as this has been shown to be a practical proposition when the seed is carefully packed in desiccators in an atmosphere of CO_2. In this connexion the linking up and extension of the four existing sugar-cane breeding stations in Australia, Barbados, India, and Mauritius should suffice for the needs of the British Empire.

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(*Received May 26, 1934*)

FIG. 1. A crossing-lantern in use in Mauritius. The glass lantern is lowered over the ♀ inflorescence or arrow in the field, the cut ♂ arrows used being preserved in SO_2-solution contained in the bamboo pot shown

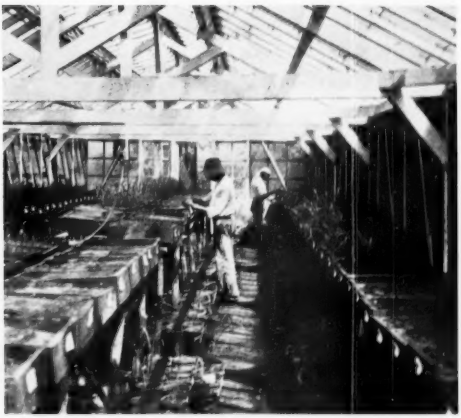

FIG. 2. Forcing young seedlings in a green-house. Each box shown contains the seeds of a separate cross

FIG. 3. Young seedlings transplanted from pots to the field

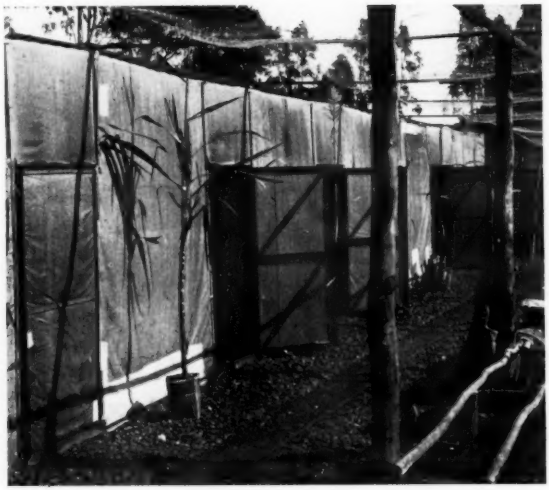

FIG. 4. A series of large calico cages used for protecting crosses

FIG. 5. Raising seedlings in boxes in the open

THE ROOT-SYSTEM OF *COFFEA ARABICA*

Pt. III. THE SPATIAL DISTRIBUTION OF THE ABSORBING AREA OF THE ROOT

F. J. NUTMAN

(*East African Agricultural Research Station, Amani, Tanganyika*)

WITH PLATES 8, 9 AND 10

IN Parts I and II of this series no attempt was made to obtain quantitative data. The root-types figured were defined by the appearance of the system in vertical section, and the distribution of feeder-roots was indicated by scale-drawings. It is of obvious importance that such data be supplemented by quantitative measurements, especially since information as to the actual absorbing area of roots appears to be almost entirely lacking.

Root-studies, in my opinion, should comprise, firstly, the morphological description of the root-system as a whole, together with its range of variation under the influence of external factors; and, secondly, the measurement of the actual absorbing area of the roots, as well as the distribution, within the root-system, of the absorbing area per unit bulk of soil.

Certain attempts to obtain quantitative data on root-distribution have involved the weighing of the roots in unit bulk of soil, or of those occupying any given soil horizon. In this connexion it must be kept clearly in mind that the roots of plants serve other functions than that of absorption. The main permanents of coffee, for example, serve (1) for anchorage, (2) as storage organs, and (3) as a conducting framework carrying the feeder-roots. It is apparent that the main roots are influenced, as to their size and weight, by storage and mechanical considerations, whereas no such influences affect the feeder-roots, which have no function save that of absorption; the latter are thin and delicate, and so light in weight that one inch of main root, of average thickness, will outweigh tens of thousands of feeders. For example, in cube 2, 3 of tree *D*, the length of feeder-roots present totals 227·28 m.; with a dry weight of just 1 gm. Thus they do not affect the weight of the roots as a whole to any appreciable extent. Any comparison involving weights of roots will be uninfluenced by the feeder-roots, and will describe, not merely the distribution of the main permanents, but the distribution of their weights, which is a rather different matter. It is very noticeable how much thicker and heavier the main roots become near the trunk of the tree: and the weights there recorded will be much greater than those nearer the periphery of the root-system, due, largely, to the structure developed to serve the anchoring function of these roots.

The problem of defining the distribution, and of measuring the total area of the feeder-roots appears analogous to the determination of the total leaf-area of a plant: the roots being the subterranean, as the leaves are the above-ground, absorbing organs. No one would suggest that an estimate of the leaf-area of a plant or even of its gross morphological

characteristics could well be obtained from a record of the distribution in space of the weight of the above-ground parts. The exchange of gases between plant and atmosphere is facilitated by the expansion of area due to the leaves, whereby the area per unit mass of plant-material is increased. The ramifications of the roots and root-hairs may also be considered to be directed to the same end: the increase of surface per unit amount of material. In other words, the most important feature of the root-system, as of the leafy portion of the tree, is its surface. And to measure the weight of the material, and not the area of its expanded surface, appears to me to be disregarding the main function of the root-system, namely, absorption.

As a further example of the limitations of the weighing method may be cited the two trees illustrated in Figs. 3 and 4 (Plate 9). It is apparent that the main difference between the two is that one has many more feeding-roots. By the method of weighing, these trees would be indistinguishable, whereas the absorbing area of one is many times greater than that of the other. In the trees figured the difference is enough to account for the successful survival of the one, and the impending death of the other.

Attempts have also been made, by means of grading the roots between arbitrary diameter limits, to adapt the weighing method to yield results which bear more relation to the absorptive capacity of the roots [1]. This is an advance of some importance, as the larger errors due to the distribution of the weights of the main permanents are discounted. But even so, the results leave much to be desired. As previously stated, 227·28 m. of *C. arabica* feeder-roots weigh only 1 gm. and small errors in grading will result in figures of considerable inaccuracy. In addition, the weights of the roots in any given grade give little clue to the understanding of their total absorptive area.

It is therefore to be concluded that the main purpose of root-studies is not served by any method involving the weighing of roots. Actual measurements of length of feeding-roots were therefore substituted.

Technique.—A trench was excavated alongside each experimental tree with one face 8–9 in. from the trunk. By means of levels and straight-edges this face was then trimmed to be plane and vertical, and exactly 6 in. from the centre of the trunk. A grid of string of 1 ft. mesh was then erected, with one vertical line 6 in. from the projection, on the face of a vertical line passing through the centre of the trunk. A further line, on the soil surface, was pegged out so as to be 1 ft. from the soil face.

The soil was then washed away in 1-ft. cubes by a jet of water of $\frac{1}{16}$ in. diameter and at 10 lb./sq. in. pressure. By means of a set-square, rule, and plumb-lines it was found possible to ensure that each cube was accurately excavated. All the soil washed away was carefully examined for the presence of broken rootlets, and all the roots from each cube were collected, washed, labelled, and preserved in dilute formalin solution.

It was not found possible to carry the work below 5 ft. from the surface or further than 3 ft. 6 in. from the trunk of the tree, since the time available was limited. However, an accurate idea of root-concentrations over the greater part of the root-system should be given. In Fig. 1 can be seen a photograph of a root-system similar to those studied. Methods

of excavating the soil cubes other than by the use of water were tried. Steel boxes of uniform size were forced into the soil and the contents removed. Cutting the cubes by means of a saw, or by digging, was attempted, but these methods were abandoned for one reason or another.

The measurement of the total length of feeding-roots in each soil cube was carried out as follows by trained and adequately supervised African assistants. The pickled roots were placed in a large dish of water, and the individual feeders were separated and placed in long rows on lined paper, a dot marking the end of one rootlet and the beginning of the next. Eventually, by a count of the interspaces between these dots, and by measuring the total length of the lines, the number and length of the feeders can be obtained. This, on occasion, may amount to 150,000 rootlets totalling 580 metres in one cubic foot of soil.

Material.—The trees selected were 3-year-old *C. arabica*, grown in the Burka portion of Area X (Engare Olmotonyi). [The soil was described in Part I in this *Journal*, 1933, **1**, 281–2.] They were in good heart and each was carrying 30–40 lb. of green cherry, equivalent to about 12 lb. of parchment coffee. The general appearance of the trees can be seen from Fig. 2, and that of the root-system from Fig. 1 (Plate 8).

Two trees of this type were excavated that were selected as being examples of young, healthy trees, which had not yet borne a crop and hence had suffered no ill effects from dieback. In considering the figures to be presented for spatial root-distribution, it must be remembered that the roots had not attained their maximum depth-growth, nor had the system, in all probability, developed its full root-concentration at the periphery. It is probable that in a year or so the root-concentrations would become more even, with depth and with distance from the trunk, in the absence of damage due to dieback.

In addition, two trees (*C* and *D*) similar in all respects, were taken which had had the whole of the leaves stripped 6 weeks before in an attempt to induce dieback. As no visible effect had been produced by the time of excavation, data from these trees are included.

These trees were all excavated during the period May 20–June 12, 1933, subsequent to a period of increased root-growth in the surface soil.

Results.—The results are expressed, firstly, as the *concentration* of feeding-roots in unit volume of soil; the concentration being given as the total length of feeding-roots in metres in one cubic foot of soil. The average diameter of a feeder and the concentration of root-hairs thereon is approximately constant over the whole root-system, so that these figures are proportional, as nearly as may be, to the actual absorbing area.

From this can be calculated the total amount of roots at any distance from the tree-trunk, by treating each cube as being a portion of a solid ring, of 1 ft. square section whose centre is at the axis of the tree. By summation the total length of the roots is given. This figure is a minimum. The central core of 1-ft. diameter is ignored, as are all roots more distant horizontally than 3 ft. 6 in. from the trunk, as well as all those below 5 ft. in depth.

An eye estimate of the proportion of roots ignored is 20 per cent.

TABLE 1. *Tree A. Concentration of Feeding-roots in the Soil*

The figures represent the total length of feeding-roots (in metres) contained in each cubic foot of soil.

Depth ft.	*Distance from trunk*		
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*
1	138·23	16·81	0
2	109·53	127·10	100·76
3	156·46	91·19	183·21
4	80·57	91·69	66·07
5	81·76	55·69	21·84

TABLE 2. *Tree A. Roots of Whole Tree (calculated from above)*

The figures represent the total length of feeding-roots (in metres) contained in rings of 1 ft. sq. section round the axis of the tree at the given distances, i.e. the total amount of roots.

Depth ft.	*Distance from trunk*			
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6in.*	*2 ft. 6 in.–3 ft. 6 in.*	*Total*
1	868·5	211·2	0	1079·7
2	688·2	1597·2	1899·4	4184·8
3	983·1	1145·9	1353·7	5582·7
4	506·2	1152·2	1245·5	2903·9
5	513·7	699·7	411·7	1625·1
				Grand total 15376·2

Total length of feeding-roots of Tree A = 15·3762 km.

TABLE 3. *Tree B. Concentration of Feeding-roots*

Depth ft.	*Distance from trunk*		
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*
1	139·29	157·78	197·41
2	164·52	118·82	150·57
3	105·08	166·40	81·13
4	97·23	106·91	32·87
5	56·82	58·75	32·01

TABLE 4. *Tree B. Roots of Whole Tree*

Depth ft.	*Distance from trunk*			
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*	*Total*
1	875·2	1982·7	3721·3	6579·2
2	1033·7	1493·1	2838·4	5365·2
3	660·2	2091·0	1529·4	4280·6
4	610·9	1343·5	619·6	2574·0
5	357·0	738·3	433·8	1529·0
				Grand total 20328·1

Total length of feeding-roots of Tree B = 20·3281 km.

TABLE 5. *Tree C. Concentration of Feeding-roots*

Depth ft.	*Distance from trunk*		
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*
1	357·38	292·58	52·25
2	580·80	507·97	291·13
3	172·01	216·23	117·35
4	143·00	96·49	14·00
5	123·65	77·98	5·36

TABLE 6. *Tree C. Roots of Whole Tree*

Depth ft.	*Distance from trunk*			
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*	*Total*
1	2245·5	3676·7	985·0	6907·2
2	3649·3	6383·4	5488·0	15520·7
3	1080·8	2717·2	2212·1	6010·1
4	898·5	1212·5	263·9	2374·9
5	776·9	979·9	101·0	1857·8
			Grand total	32670·7

Total length of feeding-roots of Tree *C* = 32·6707 km.

TABLE 7. *Tree D. Concentration of Feeding-roots*

Depth ft.	*Distance from trunk*		
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*
1	75·16	104·34	76·28
2	164·34	233·25	227·28
3	124·16	101·40	168·05
4	63·50	76·00	95·43
5	105·18	173·00	69·44

TABLE 8. *Tree D. Roots of Whole Tree*

Depth ft.	*Distance from trunk*			
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*	*Total*
1	472·2	1311·2	1437·9	3221·2
2	1032·6	2931·1	4284·4	8248·2
3	780·1	1274·2	3167·9	5222·2
4	399·0	955·2	1798·9	3152·9
5	660·9	2174·0	1309·0	4143·9
			Grand total	23988·4

Total length of feeding-roots of Tree *D* = 23·9884 km.

TABLE 9. *Average of A, B, C, and D. Concentration of Feeding-roots*

Depth ft.	*Distance from trunk*		
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*
1	177·52	142·88	80·74
2	254·80	264·79	192·91
3	139·43	143·81	137·44
4	71·08	92·78	52·09
5	66·85	91·35	29·91

TABLE 10. *Average of A, B, C, and D*

Depth ft.	*Distance from trunk*			
	6 in.–1 ft. 6 in.	*1 ft. 6 in.–2 ft. 6 in.*	*2 ft. 6 in.–3 ft. 6 in.*	*Total*
1	1115·4	1794·1	1522·0	4431·5
2	1601·0	3098·8	3636·5	8336·3
3	876·4	1805·7	2590·9	5273·0
4	446·6	1165·0	981·9	2593·5
5	420·0	1147·0	263·8	2130·8
			Grand total	22765·1

Total length of feeding-roots, on average of 4 trees = 22·7651 km.

The Total Absorptive Area of the Roots

Measurement of representative samples of feeder-roots from the trees excavated shows that the average diameter approximates to 0·7 mm. The total surface of the feeders, excluding that due to the presence of root-hairs, can thus be calculated.

The increase in area due to the presence of root-hairs has been calculated as follows. From a number of representative feeders, sections less than 1 cell thick were cut. The total number of epidermal cells, and the total number of hairs were determined for each section, and the percentage of cells which have produced hairs was found. In addition, the ratio of length to diameter of the root-hairs was determined. On the average 24 per cent. of the epidermal cells are hairs, and the hairs are eleven times as long as they are wide.

Now, for a section with x epidermal cells of average diameter a, the surface area will approximate to a^2x, and the area of a single root-hair will be nearly $2\pi\frac{a}{2}\times 11a+a^2$. And since $x\frac{24}{100}$ cells bear root-hairs, the total area of these will be $24\frac{x}{200}a^2(1+11\pi)$. Since the epidermal area (ignoring hairs) is a^2x, the increase in surface due to the presence of these is

$$\frac{24\frac{x}{100}(11\pi+1)a^2}{a^2x}$$

i.e. $\frac{24}{100}\times 35{\cdot}5 = 8{\cdot}5$ times.

Therefore the total absorptive area is

$$8{\cdot}5y + \frac{76}{100}y = 9{\cdot}26y,$$

where y is the superficial area of the feeder-roots.

TABLE 11. *Area of Roots*

Tree	*Total length*	*Area of feeding-roots*	*Area of root-hairs*	*Total absorbing area of root*
	km.	sq. m.	sq. m.	sq. m.
A	15·3762	33·8	287	313
B	20·3281	44·7	380	414
C	32·6707	71·8	611	665
D	23·9884	52·8	448	489
Average	22·7651	50·1	426	464

TABLE 12. *Concentrations of Feeding-roots (expressed as percentages of the maxima) in the Various Soil Horizons*

Depth ft.	*Tree A*	*Tree B*	*Tree C*	*Tree D*	*Average*
0–1	36	*100*	50	50	58
1–2	78	88	*100*	*100*	*100*
2–3	*100*	71	36	63	61
3–4	55	48	18	38	31
4–5	37	28	15	56	27

TABLE 13. *Amounts of Feeding-roots (expressed as percentages of the total) in the Various Layers*

Depth ft.	*Tree A*	*Tree B*	*Tree C*	*Tree D*	*Average*
0–1	7·0	32·4	22·1	13·5	19·0
1–2	27·2	26·4	47·4	34·3	36·6
2–3	36·4	21·1	18·4	21·8	23·2
3–4	18·9	12·7	7·3	13·1	11·0
4–5	10·6	7·5	5·7	17·2	9·3

TABLE 14. *Amounts of Feeding-roots (expressed as percentages of the total) Below Each Level*

Depth ft.	*Tree A*	*Tree B*	*Tree C*	*Tree D*	*Average*
0	100	100	100	100	100
1	93	68	78	86	81
2	66	41	31	52	42
3	29	20	13	30	19
4	11	8	6	17	9

Discussion

It is realized that two cogent criticisms of the foregoing results can be made.

Firstly, a single section 5 ft. × 3 ft. 6 in. × 1 ft. is taken to be representative of the root-system as a whole, in the absence of numerical evidence as to the evenness of distribution of the feeder-roots within that system. Although in many areas this would undoubtedly invalidate any conclusions, yet in this district I think that the results as presented have approximate relation to facts. The soil here is unusually uniform: termite galleries, mole runs, local concentrations of richer soil, &c., being far from common. Consequently local concentrations of roots are rare. From exposures of many root-systems their uniformity has been amply demonstrated. In addition, the trees studied were young and in good heart and had not borne a previous crop. Consequently no damage due to dieback in previous years had taken place.

Secondly, it might be objected that conclusions have been drawn on too small a number of trees. It was not possible to excavate more than four complete sections for a variety of reasons: and whilst the criticism is admittedly justified, certain considerations make it appear advisable that the results should be presented.

I am unaware of any previous measurements giving an approximation to the absorbing area of the roots of a tree. Consequently the foregoing data, even if they only give the order of magnitude of that area, appear to be of some value.

To carry out a fully adequate study by the methods adopted would necessitate the employment of a very large body of trained labour for root-measurement: and a long time spent in the field. Resources in both directions were limited; therefore the data obtained here must perforce suffice, and the question of how far the trees examined are representative must be left for further research to determine.

The Distribution of the Absorbing Surface

It should be clearly understood that the foregoing results refer to the root-system of coffee in the district investigated, and are not necessarily applicable to other areas. I think it probable, however, that the main features of the distribution would be similar in other areas where the rooting habit has been shown to be similar, e.g. Kikafu, Rasha Rasha, Ol Doinyo Sambu—or in any other area where the soil is deep, well-aerated and with a reaction approaching neutrality. Figs. 5 and 6 (Plates 9) represent graphically the information contained in Tables 9 and 10, i.e. the average spatial distribution of the feeding-roots of the four trees studied. It will be seen that the concentration of the feeding-roots falls off from the centre of the system towards the periphery, and that, for all distances from the trunk, the greatest concentration of roots is at the 1–2 ft. level, followed in turn by the 2–3 ft. and the 0–1 ft. layers. The total amount of roots, on the other hand, increases as the periphery is approached, the distribution in depth being as before.

Table 14 shows the percentages of the whole root-system below each

foot from the surface. These figures should be slightly higher, since there are roots below 5 ft. It should, I think, finally dispose of the prevalent idea that *C. arabica* is essentially a surface-rooting plant. That in some districts (i.e. Sanya, the East Usambaras, and Kiambu) the bulk of the feeders are in the surface soil is certain. But in deep, neutral soils such as that studied it will be seen that not only does the plant produce main roots and feeders in the subsoil, but by far the greater portion of the absorbing surface is in the soil layers at a greater depth than one foot from the surface.

Water-absorption by the Roots

In view of the evidence put forward, the total absorbing area of the roots of the coffee-tree can be taken to be of the order of 400–500 sq. m. This absorbing area, even in young trees, is distributed fairly evenly through the soil (in this district), and with older trees the concentration of roots in the deeper soil layers will almost certainly increase, thus increasing the evenness of the distribution.

This has some bearing on the rate of absorption of water from the soil. Whilst accurate evidence as to the water relations of coffee is lacking, weighings of potted plants give results which for trees such as those worked on, are of the order of 12 litres of water per tree per 12 hours of daylight. That the leaves are capable of transpiring at much higher rates can be seen from the water losses of cut branches where rates (calculated on the basis of a tree of 5,300 leaves) of up to 3·5 litres per hour have been recorded. This is confirmed by the considerable reduction in pressure demonstrable in the wood of a transpiring coffee-tree. This pressure may be as low as 28 cm. of mercury, i.e. 40 cm. below the atmospheric pressure at an altitude of 3,000 ft. It is thus apparent that this rate of 1 litre per hour represents the maximum absorptive capacity of the root-system: i.e., the maximum rate of entry of water into the root approximates to 2·5 c.c. per square metre per hour. This figure is unexpectedly low.

It is not readily to be expected that the maximum rate of passage of water into the *root-hair* is so low as the value given above; and it would appear more probable that the rate of ingress of water is limited by some other factor. Such resistance to the flow of water might be:

1. The rate of movement of water in the soil. A zone of dry soil might be formed immediately round each root-hair, and the rate of movement of water towards this drier zone might be slow enough to limit intake. This undoubtedly operates in dry soil, but not, I think, normally, since complete soaking of the soil does not, appreciably, influence transpiration.

2. The rate of movement of water through the cortical tissues of the root.

In the absence of any experimental evidence it appears futile to discuss this possibility.

3. Entry into the lumena of the vessels. This appears worthy of consideration. From measurements of the cross-sections of the xylem groups in the rootlets the linear measurement of the vessels in contact with living

cells averages 0·12 mm. On this basis the area of the outer walls of the xylem cells in tree A will be 15,376,200 × 0·12 sq. mm., i.e. 1·85 sq. m. Through this area 1 litre of water passes per hour in order to maintain transpiration, giving a rate of 595 c.c./m.²/hour. This is 170 times greater than the rate through the root-hair surface of the same tree.

It appears worthy of emphasis that the rate of entry of water into the xylem vessels of the rootlets controls the transference of water from the soil to the above-ground organs. Scott and Priestley [2] arrived at a conclusion which is in some respects similar, in that they considered that the importance of the root-hairs had been over-emphasized. Whereas in dry soils the maximum capacity of the root-hair for absorption may be called upon, it appears to me to be possible that the main function of the root-hairs is to increase the bulk of soil in immediate contact with the roots, in order that the water absorbed may be extracted evenly from the soil mass. Thus the rate of removal of water from any point is comparatively slow, and the formation of a dry soil zone round the roots is rendered less likely.

Acknowledgement

I wish to record my thanks to Mr. F. A. F. Schmid, of Arusha, who has provided material and labour for this, as for other, investigations.

Summary

1. Methods of obtaining quantitative data on root-distribution are criticized and reasons given for the choice of linear measurement of the feeding-rootlets. The technique adopted is described.

2. Figures are presented for the feeder-root concentrations in sections of 1-ft. thickness through the root-systems of four 3-year-old *C. arabica* trees for depths of 0–5 ft. from the surface and 6 in.–3 ft. 6 in. from the trunk. From this is calculated the total length of the feeder-roots.

3. The surface of the roots (including root-hairs) is computed and is considered in relation to the rate of entry of water per unit area of root-surface. This is very low, and it is suggested that the rate of entry of water into the xylem cells of the roots might be the limiting factor in the rate of entry of water into the plant.

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(*Received May 12, 1934*)

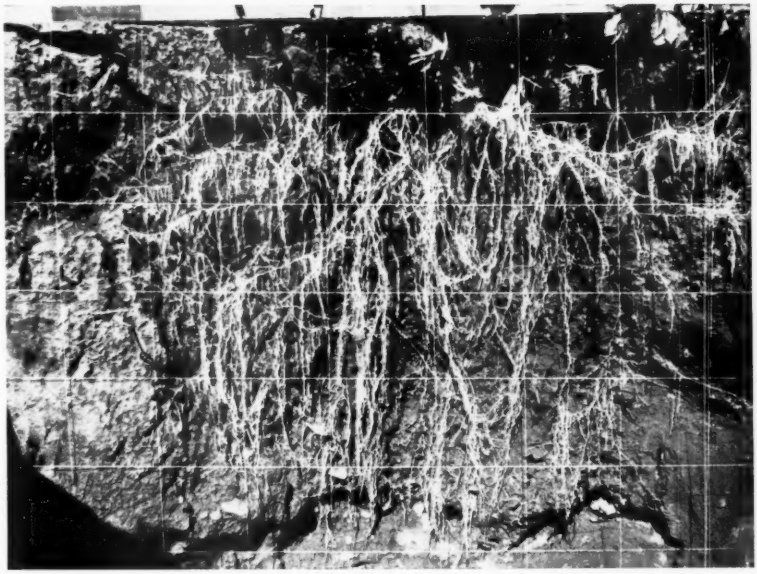

FIG. 1. Root system of three-year-old *C. arabica*. The strings are 1 foot apart

FIG. 2. Three-year-old *C. arabica*

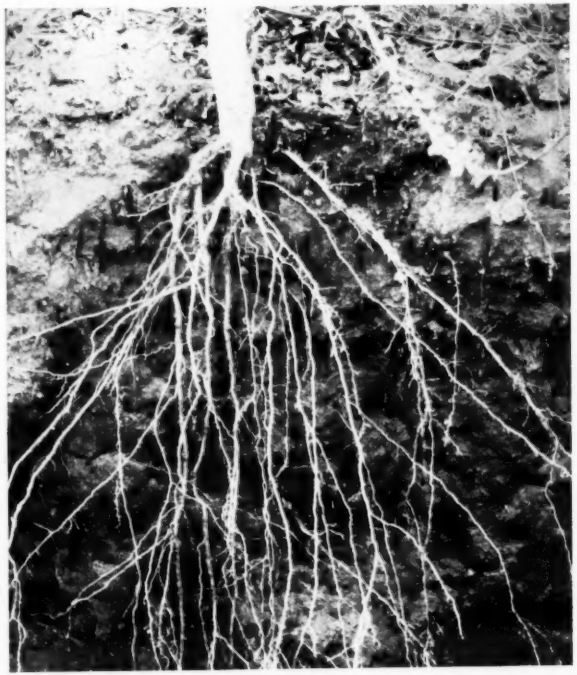

FIG. 3. Root system of two-and-a-half-year-old *C. arabica* after overbearing

FIG. 4. Root system of two-and-a-half-year-old *C. arabica*, showing little overbearing

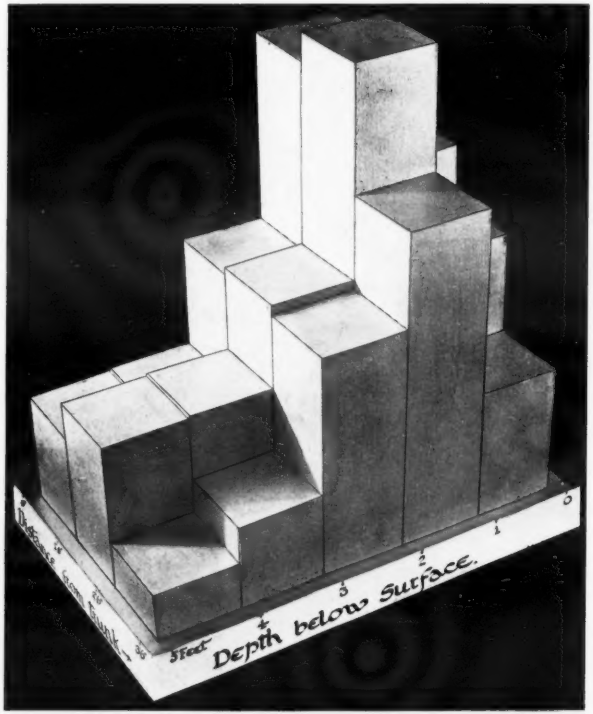

FIG. 6

Total amount of feeding-roots (total length)

Three-dimensional diagram of Table 10. Each vertical height represents the total amount of roots at the given depth and distance from the trunk

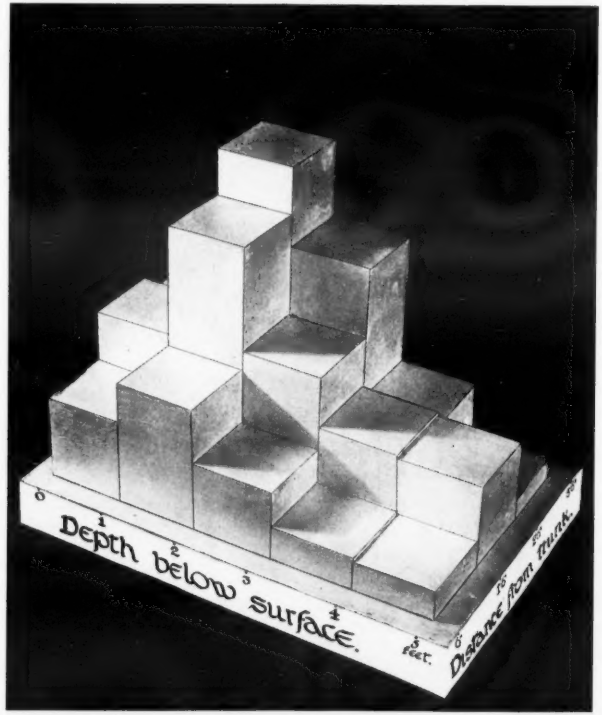

FIG. 5

Concentrations of feeding-roots

Three-dimensional diagram of Table 9, vertical heights representing the concentration of feeding-roots at each depth and distance from the trunk

THE COFFEE-PLANTING INDUSTRY IN SOUTH INDIA

L. C. COLEMAN

ALTHOUGH in recent years coffee has had to give way to tea as the most important plantation industry in South India, it still retains an importance which cannot be estimated upon the basis of acreage or value of crop only.

The coffee plant was introduced to the west coast of India from Arabia during the latter part of the seventeenth century and into Mysore State, according to tradition, by a Muhammadan pilgrim returning from Mecca early in that century. It remained insignificant, being grown by Indian cultivators in small patches, until the first part of the nineteenth century, when, through European capital and energy, the beginnings of a plantation industry were made in practically all the important coffee districts and in others where, during the past thirty or forty years, coffee has largely been replaced by tea. The industry developed very rapidly towards the end of the nineteenth century, and in 1896 an area of 304,447 acres was officially reported to be under coffee in Madras Presidency, Coorg, and in the Indian States of Mysore, Travancore, and Cochin. The peak of the industry, however, as judged by export figures, was reached much earlier, as the exports of 1894–5 were only a little over one-half those of 1871–2.

The early estates were, for the most part, opened up in regions of heavy rainfall, and many of the pioneers, who had had previous experience in Ceylon, introduced the Ceylon methods of clean weeding and growth in the open, but with disastrous results. Many of these estates, heavily attacked by white borer, leaf-disease, and green bug, and with their surface-soil rapidly removed by wash, soon ceased to pay, and were either abandoned or the coffee on them was replaced by tea. These factors, along with a slump in prices, reduced the reported area in 1919–20 to 116,411 acres. Since then there appears to have been a gradual increase. The statistics of coffee acreage are anything but accurate, and frequently the area reported to be under coffee includes unplanted jungle. It seems, however, fairly certain that the present planted area in South India is around 150,000 acres, of which about one-half is in Mysore State.

It would be unsafe to attempt to predict the future of the coffee industry. Now, when agriculture in general is passing through a period of profound depression, there is certainly no evidence of any rapid expansion in area. There are, however, indications that, with a return to more normal conditions, development will start afresh. For one thing, the trials of *Coffea robusta* during the past twenty years, more especially in the lower elevations where through the prevalence of disease and other causes the growing of *Coffea arabica* has ceased to be profitable, leads one to expect the development of a very considerable area under this more vigorous species. Further, the breeding-experiments of the Mysore Coffee Experiment Station already hold out great promise of producing much more vigorous and disease-resistant strains of *C. arabica* and of

hybrids, which should make the growth of coffee profitable under much more varied conditions than is possible at present.

Notwithstanding its present comparatively small area in South India, coffee has still a much wider territorial range than tea. Moreover, the fact that its preparation for the market requires a very small expenditure of capital for machinery has left it pre-eminently as the plantation crop for the small individual grower, as opposed to the large company. This is very striking in Mysore State, where a large part of the total area is cultivated by Indian planters owning individually 25 acres or less. Even the estates of European planters are small compared with those in some other coffee-growing countries, an average size being perhaps between 200 and 300 acres.

C. arabica, which has been heretofore the only species cultivated on a plantation scale, has been gradually replaced by *C. robusta* at the lower elevations and in the districts most subject to disease. This replacement is still going on rather steadily, and it seems probable that the area under coffee may expand by the planting of *C. robusta* in districts where coffee is not now being grown at all.

Coffee is confined to the hilly areas of comparatively heavy rainfall comprised in the Western and Eastern Ghats and their offshoots. Attempts made some years ago to grow coffee under irrigation in areas of low rainfall, such as Bangalore in Mysore State, ended in failure. Successful plantings have almost invariably been made on what was originally fairly heavy jungle, although cases are not wanting of successful estates, or parts of estates, having been developed on land under scrub jungle or even grass.

As might be expected from its comparatively wide distribution, coffee is grown under very varying conditions of elevation, soil, and rainfall. In the Mysore State, for example, the elevation of coffee estates varies between 2,500 and 4,500 feet, the higher elevations being the more suitable in respect of quality of crop, freedom from disease, and average yield. In the Nilgiris and the Billigirirangans, coffee is grown up to 5,500 feet, but at such high elevations it has, for the most part, been replaced by tea. In two other important coffee districts, the Shevaroys and the Annamalais, the elevation is between 3,500 and 4,000 feet.

The rainfall in coffee districts varies widely both in amount and distribution. In the western districts of Mysore and Coorg, the rainfall is largely confined to the period of the south-west monsoon, June–September, though blossoming follows the first showers in March or April, which succeed drought conditions lasting 3–5 months. The more easterly districts receive much more rain, which is derived from both the south-west and north-east monsoons. The annual rainfall varies between 50 and 150 inches. High rainfall of over 100 in. is, in general, considered unsuitable for coffee, but that is, I believe, largely because it is usually associated with severe attacks of such diseases as black rot, leaf-disease, and dieback. With the methods of disease-control recently introduced, there seems no reason why *arabica* coffee should not be grown with profit in many areas where it has been abandoned largely owing to conditions associated with heavy rainfall.

Whereas the common types of soil are the red gravelly loams characteristic of much of the wooded areas of our hilly regions, we also find considerable areas under fairly stiff clays, and others characterized by large amounts of rock outcrops. On the whole, however, a friable loam, well supplied with humus and allowing of easy drainage, may be regarded as the most suitable for coffee. The development of more hardy strains and varieties and the introduction of *C. robusta* are likely to extend very considerably the choice of soils for coffee cultivation.

Early Scientific Work

The earliest strictly scientific work on coffee in South India was that of Lehmann [1], who, during the period 1898–1908, started work on the manuring of coffee and the factors determining quality. Work was continued by Anstead, and results of great value were obtained, although the lack of plots under the direct control of the investigators was a great handicap. This was remedied in 1919 by the establishment of a small experiment station at Sidapur, in Coorg, which was under the charge of Anstead until 1922 and afterwards under Munro [2, 3]. This station closed down in 1926, and a year after the Mysore State Coffee Experiment Station was founded at Balehonnur in the Kadur district of Mysore.

In the earlier period the Planters' Associations of Mysore and Coorg appointed two assistant scientific officers to work under the direction of Anstead. The longer of these appointments lasted for about five years from 1912, and the principal achievement was the study of spraying against black rot by Frattini [4]. Anstead's earlier work was mainly of an advisory nature, but he found time to investigate with Pittock [5] the composition of the coffee fruit during development and the variability of yield of individual bushes [6, 7].

With the opening of the Sidapur Experiment Station it was possible to extend investigations on manuring, cultivation, and spraying, and the main results then obtained were summarized by Munro in 1926 [8]. The value of spraying was emphasized; manuring experiments gave much less definite results, but the value of green dressings and bulk composts was indicated. Some work on selection was started during this period, and the more promising seedling families were transferred to the Mysore Station.

The Mysore Coffee Experiment Station

In 1925 scientific work on coffee entered a new phase with the establishment of the Mysore Coffee Experiment Station [9]. This Station has a total area of over 200 acres, of which about 80 acres are under old coffee, 20 acres under young coffee (mostly selections), and the remainder is still jungle reserved for future extensions. It has an excellent laboratory, where plant-breeding, the study of diseases, and the preparation of samples for chemical analysis are carried out. The chemical control is carried out under the supervision of the Agricultural Chemist in the well-equipped departmental laboratories in Bangalore.

A most interesting feature of the work during the past six years has been

the establishment of close co-operation of practically all the coffee-planting interests of South India in support of the work of the Station. The main budget of the Station is provided in equal parts from Mysore State funds and a small acreage cess on coffee land in the State. The United Planters' Association has provided the services of a European scientific officer and of an Indian assistant, an arrangement which has provided a most valuable addition to the staff of the Station. The interest of coffee-planters in general in the work of the Station has been further ensured and maintained by the establishment of an advisory committee of five coffee-planters, who are associated with the Director of Agriculture in Mysore in the supervision of the Station's work. This committee, consisting of representatives of the Indian and European planters of Mysore and of the United Planters' Association of Southern India, is calculated to keep the activities of the Station in close touch with the needs of the industry.

A general programme of work to extend over twenty years was laid down in 1928 and approved by Government; it should go far to ensure that continuity of effort without which the time and money devoted to research would largely be wasted. The programme envisaged the following chief lines of investigation:

(*a*) *Chemical and soil investigations.*—These include a thorough study of the plant-food requirements of the coffee plant under South Indian conditions and a special investigation of the effects of soil acidity upon growth. Later on it is hoped to study the possible effect of manuring on coffee quality.

(*b*) *Plant diseases and insect pests.*—Plant diseases and insect pests have without doubt influenced the coffee industry of South India more than any other single set of factors. It was largely green bug (*Coccus viridis*, Green) and leaf-disease (*Hemileia vastatrix*) which led to the extensive abandonment of coffee cultivation in the Nilgiris towards the end of the nineteenth century, and mainly black rot (*Corticium koleroga*) which led to its abandonment in the western areas of Mysore and Coorg along the Western Ghats, and its replacement by cardamoms and, to a lesser extent, by tea. White borer (*Xylotrechus quadripes*, Chever) and leaf-disease have taken a heavy toll from coffee estates in the lower elevations of Mysore and South Coorg. More recently, dieback (*Colletotrichum coffeanum*) has greatly reduced crop-yields and weakened coffee plants over very large areas; and within the last two years it has been discovered that eel-worms are a very serious source of failure and general unthriftiness of coffee in certain important districts.

(*c*) *Plant-breeding.*—This is perhaps the most important activity of the Coffee Station. Obviously, with a perennial crop like coffee progress must be slow, but an effort has been made to obtain results of practical value at the earliest possible moment by using material so abundantly available on coffee estates throughout South India and from other parts of the world. Associated with this breeding-work has been an investigation of the possibilities of using grafting methods for establishing selected strains of *arabica* coffee on more vigorous root-stocks, such as those derived from *C. robusta* and certain hybrids of *C. arabica* and *C. liberica*,

which have been grown on a small scale for many years in Mysore. Although most attention has been given to the improvement of *C. arabica* by selection and hybridization, the fact that *C. robusta* is likely to be of increasing importance in the future has led to the development of selection work on this species also, whilst the presence in our extensive collections of promising races of *C. congensis* and *C. uganda* will allow for their early inclusion in our programme.

Review of Results so far Obtained

A period of eight years in the history of an Experiment Station dealing with a crop such as coffee is perhaps too short a time to warrant the expectation of results of striking value. However, the effects of the Station's activities are already widely apparent and some of the results obtained are undoubtedly of first-class importance.

(*a*) Although the results so far obtained on soils and manuring hardly warrant a generalization on the manurial requirements of coffee in South India as a whole, yet they have largely revolutionized manurial practice. In so far as these results have shown returns from the manuring of coffee, they have indicated quite clearly the advantages of the use of concentrated artificial fertilizers, such as ammonium sulphate and superphosphate, over the less concentrated organic fertilizers, such as oil-cakes and bone-meal, which were in almost universal use for coffee even ten years ago. The reduction in price of artificial fertilizers and the great saving in transport charges have had much to do with this change, but the evidence obtained at the Station that 'artificials' give better returns per fertilizer unit than the less concentrated organic forms has greatly influenced the change. Most of the manures now supplied conform with the formulae worked out by Dr. Narasimha Iyengar, Agricultural Chemist, Mysore Agricultural Department, on the basis of his experimental work [10]. The belief that organic fertilizers will have some special effect owing to their content of organic matter seems unfounded. The quantity of organic matter added in the comparatively small amounts applied is infinitesimal in comparison with the amount yearly added to the soil through the fall of leaves from coffee plants and shade trees.

An interesting long-period experiment on the effect of pH reaction on the growth of coffee plants has already given clear indications that markedly acid or alkaline reactions in the soil are detrimental to the growth of coffee. This, along with the institution of pH determinations in the field by the chemical staff of the Department, has made much more definite the advice given to planters on the subject of liming.

(*b*) The investigation of plant-diseases and their control has given much more striking results. Long before the Station was established, one of the more important diseases, black rot, had been investigated by the author and his colleagues [11]; its life-history and methods of spread had been worked out; and it had been established both by our own trials and by those of Frattini that the disease could be very readily controlled by spraying with Bordeaux mixture. Recently, the State Mycologist, Mr. M. J. Narasimhan, has cleared up a number of obscure points in

connexion with this disease [12]. Although there was evidence that spraying with Bordeaux mixture would give an economic control of the more important leaf-disease, caused by *Hemileia vastatrix*, the course of the disease was not accurately known and the conditions governing the appearance of severe outbreaks were obscure. Mr. W. W. Mayne, Coffee Scientific Officer, was entrusted with an intensive study of this disease in October 1928, and the results he has obtained are of outstanding importance for the South Indian coffee industry.

In the first place Mr. Mayne developed a technique for the statistical study of the incidence of leaf-disease throughout the year. His studies, which extended over two successive years, enabled him with some accuracy to deduce the climatic conditions, i.e. atmospheric moisture and rainfall, that conduce every year to the serious increase in this disease, which is always present to a greater or less extent on every coffee estate in South India [13] There still remain to be investigated many of the environmental conditions favouring the spread of leaf-disease. One of the most important factors is undoubtedly temperature, for the study of cultures in the laboratory has already shown that temperatures below a certain minimum inhibit the formation of spores. Light has also been found to influence the germination of spores and the amount of spores developed, and hence also the establishment of fresh infections.

Perhaps the most striking result of Mr. Mayne's work on *Hemileia* has been the establishment of the existence of two physiological strains of this fungus [14]. This discovery, which is of the greatest value in testing new *arabica* selections and new hybrids for resistance to leaf-disease, has at the same time dispelled obscurity concerning the resistance of the valuable selection Kent *arabica*, which has been widely planted during the past ten years both in South India and in East Africa. This selection, which is due to the well-known Mysore coffee-planter, Mr. L. P. Kent, has been commonly found, particularly during the first two or three years of growth, more resistant to the attacks of *Hemileia vastatrix* than are the Coorg *arabica* types heretofore commonly grown, especially in Mysore and Coorg. This resistance has usually broken down later on, and for reasons that were quite obscure. Mr. Mayne has found that Kent *arabica* is highly resistant (one might say immune) to one of the two physiological strains so far isolated (strain No. 1), but highly susceptible to the other (strain No. 2). The usual Coorg *arabica* types are, on the other hand, susceptible to both strains.

In establishing and maintaining *Hemileia* strains in culture, recourse has been had to a technique originally developed by Clinton in America. It has been found that coffee-leaves, removed from the trees, can be kept alive in the laboratory for 6 weeks by immersing the petioles in tap-water contained in petri dishes, and this gives ample time, after inoculation with spores from a known source, for the development of pustules and a fresh crop of spores. This technique is now being used in the study of the resistance of coffee nursery plants to both the isolated strains of *Hemileia*. It has been found more satisfactory to leave the young plants in nursery for eighteen months rather than the usual 6–8 months, but the eventual saving of time and space will be enormous. Hereafter, only

such selections as have shown themselves by this laboratory test to be resistant to the two *Hemileia* strains will be planted out in the field.

Space will only permit a passing reference to other serious diseases of coffee in South India, such as dieback and root-rot, with which are associated various fungi, the most important being *Fomes lamaoensis*. It must suffice to say that these are receiving continuous attention and that it is already fairly clear that dieback is susceptible to control by sprays used for controlling the two important diseases, black-rot and leaf-disease.

To the practical coffee-planter, the most important development in the control of coffee diseases has been the introduction of spraying, mainly against black rot and leaf-disease, but also with considerable success against dieback.

The first spraying experiments were carried out by the Mysore Agricultural Department in 1911, and they were followed by those of Frattini in 1916–17 [4] and those of Munro from 1922 to 1926 [15]. In addition, some Mysore coffee-planters carried out, at my instance, spraying tests on leaf-disease with a fair measure of success [16].

On the establishment of the Mysore Coffee Experiment Station, a very extensive series of spraying experiments was started dealing with the character of spray or dusting material to be used, the strength of solution, the inclusion of adhesives of various kinds, the time and frequency of application, and the most suitable type of sprayers including knapsack-sprayers, hand-operated sprayers, working lines of hose, and motor-sprayers [17]. It may now be considered as established that a thorough spraying with Bordeaux mixture (formula $2\frac{1}{2} : 2\frac{1}{2} : 50$) in the months of April and May, before the monsoon, ensures an almost complete control of black rot. This application combined with a similar post-monsoon spray in October gives, in most cases, a satisfactory and economic control of leaf-disease and dieback. Where leaf-disease is serious these applications lead to the retention of double the amount of leaf, as compared with unsprayed coffee, and at the same time to an average increase in crop of about 2 cwt. of coffee per acre. With trained men and with thorough supervision over the preparation and application of the mixture, the two applications can be made at a cost of approximately Rs. 25 per acre. As even under present abnormal conditions the average price of coffee on the west coast of India is about Rs. 45 per cwt., it can be seen that spraying is likely to prove very profitable. This has been fully appreciated by planters, more especially in Mysore, where in 1933 nearly one-third of the total area (over 20,000 acres) was sprayed. Figures for areas sprayed outside Mysore are not available but they must amount to a further 10,000 acres. Thus we may take it that one-fifth of the total area under coffee is now being regularly sprayed for the control of important diseases. This is a development almost wholly confined to the past ten years, and it has played an important role in enabling Indian coffee-planters, more especially in the less-favoured areas, to withstand the very severe strain of the economic depression from which this crop, along with almost all others, has suffered in recent years.

Tests have not been confined to Bordeaux mixture, and, as a matter of

fact, Burgundy mixture is fairly extensively used, more especially in areas where there are difficulties in obtaining satisfactory supplies of lime. However, careful tests conducted over a series of years at the Coffee Station show fairly conclusively that Burgundy mixture is not so effective as Bordeaux mixture. The experiments with other spray materials, e.g. lime-sulphur, and with a large number of dust fungicides have given very unsatisfactory results.

Spreaders and adhesives have been studied intensively, and although the results are not absolutely conclusive, the balance of evidence indicates that a spreader, such as lime caseinate or linseed oil, can be used with advantage. More recent trials with other vegetable oils as spreaders indicate that some of them are likely to prove quite as satisfactory as, and at the same time cheaper than, the two spreaders mentioned above, which are now in general use.

The small pressure-knapsack-sprayer, originally introduced into India over 25 years ago by the Mysore Agricultural Department and still generally used to control an important Phytophthora disease of areca-nut, has, for coffee-spraying, gradually been replaced by the so-called Headland type of sprayer, from which the spray material is pumped from a double pump, mounted on a skid, through long lines of hose (four to six in number). Small motor-sprayers working on the same general principle as the Headland sprayers are used to some extent, but the high cost of petrol in India has militated seriously against their general adoption.

Turning to the insect pests of coffee, green bug (*Coccus viridis*) was very thoroughly investigated many years ago by Dr. K. Kunhi Kannan, late Entomologist to the Mysore Agricultural Department, and myself [18]. Although it is still regarded as of considerable importance in restricted areas, it is, I think, not now generally considered a serious pest of coffee. Fairly effective control can be obtained by spraying with fish-oil and resin soap, according to a formula worked out by the Mysore Agricultural Department. Very recent work on insecticides by the Entomological Section of the Department has shown that fish-oil can be satisfactorily and economically replaced in the insecticidal soap by an oil expressed from the seeds of a common local leguminous tree, *Pongamia glabra*, and this is now being tested in the control of green bug and other sucking insects. Efforts to obtain a combined fungicidal and insecticidal spray to control this pest along with the main leaf-diseases has so far not been successful. 'Sulphemulsol', a proprietary product from Trinidad, is now under test.

White borer (*Xylotrechus quadripes*) remains the most serious pest of coffee over large areas [19]. The most satisfactory method of control is, perhaps, the regulation of shade, for egg-laying is much more abundant in sunny than in shady areas, but coupled with this must go a thorough removal every year of bored trees. The application of ovicides and larvicides to the stem, and the scrubbing of stems to remove and destroy the eggs that are laid in crevices of the bark, have given results of some promise, but have not as yet been generally adopted. Lastly, the markedly greater retention of leaves in sprayed coffee, leading as it does

to a much more effective shading of the stems, has appreciably reduced the damage done by this pest. This is an interesting case of control measures against fungous diseases proving fairly effective against a serious insect pest as well.

(*c*) *Plant-breeding*.—There has, of course, been a great deal of variety-testing and even of plant-breeding done by coffee-planters themselves, but, unfortunately, this work has with one or two exceptions left no permanent mark on the South Indian coffee industry, largely because it was not carried out with adequate care or over a sufficiently long period.

The earliest type of *arabica* coffee grown in Mysore was, apparently, the so-called 'Chick' type (after Chikmagalur, an important town in the coffee district of North Mysore), characterized mainly by the growth-habit of the primaries, which rise at a rather acute angle from the stem. Opposed to this is the Coorg type, with primaries developed at almost right angles to the stem. Of these, the former has proved much more susceptible to leaf-disease than the latter and so has been replaced by it. Of the selections which are of the typical *arabica* type, only two have been cultivated at all generally, and of these the so-called Jackson *arabica* has not lived up to its early promise and has practically disappeared from cultivation. The other, known as 'Kent' *arabica*, developed by Mr. L. P. Kent of Doddengudde Estate, Mysore, has been very widely cultivated and is generally considered to be the best *arabica* strain now available in South India. As already pointed out, its resistance to leaf-disease is only partial; moreover, it cannot be said to be a uniform strain, as seed does not breed absolutely true. A very large number of rough selections has been made by individual planters and used for multiplication on their estates. Lastly, almost every estate has its representatives of the 'Golden Drop' and Maragogype types, which originated in Brazil, and of 'Blue Mountain' from Jamaica. None of these has, under South Indian conditions, proved as valuable a type as those which have been developed here.

There are a very large number of representatives of hybrids between *C. arabica* and *C. liberica*. In some cases these have originated as chance hybrids from seed picked from *arabica* bushes growing in the neighbourhood of *liberica* plants, of which there are considerable numbers scattered through the various coffee areas. Most of them, however, are the result of definite hybridization carried out by several planters, but chiefly by Mr. J. G. Hamilton of Chandrapore Estate, Mysore, and from them a large number of the hybrids known as Netrakonda, Mockett's, Crawford's hybrids, &c., has arisen. These plants, which are usually characterized by great vegetative vigour and pronounced resistance to leaf-disease, show many other hybrid characters, e.g. malformation of beans, marked deformity of the anthers, and even of the pistils. Most of them are comparatively poor bearers and nearly all show an abnormally high proportion of empty berries in the crop, the berries being in almost every case of the general *arabica* type. All of these hybrids are highly heterozygous and only a few have been taken up seriously as a plantation crop. Perhaps the most important of these is the so-called 'Netrakonda' hybrid, of which we have a comparatively large area on the Station, and

seed of which is regularly distributed by the owners of the Netrakonda estate.

Although, as stated, these hybrid types are generally of little value for plantation purposes, they form a rich mass of material for further breeding-work. A general collection of seed from the most promising of them was made in all the coffee areas of South India during the years 1927 to 1929, and the progeny now form an important part of the breeding-material in the Station. The availability of this valuable material should greatly shorten the task of evolving strains to suit our conditions.

C. robusta has been grown on a small scale in *arabica* plantations of South India for the past thirty years. There has been, therefore, ample opportunity for natural cross-fertilization to occur between these two species, but, nevertheless, no types have come to our attention which can indubitably be regarded as *arabica-robusta* hybrids. This is probably explained by the observation that where artificial cross-fertilization has been carried out, the F_1 generation shows morphological characters that are hardly distinguishable from those of the *arabica* parent. Similar results have been obtained in Java, where *arabica* has been used as the female parent, and so far this is the only cross we have been able to make. We have already accumulated a considerable amount of material of *arabica-robusta* hybrids, none of which shows particular promise. However, the F_2 generation may provide more promising material.

In addition to this interspecific-hybrid material, there are now available on the Station almost all the *arabica* types in cultivation, as well as the progeny of selected *arabica* trees growing on estates scattered over the whole of South India. Coffee-planters have co-operated generously in supplying the Station with this material, so I think we may safely say that our collection represents the best that South India has so far produced.

The purification of the material thus collected has formed one of the main items of work during the past five years. Within this time we have obtained one generation and are just planting out the second. The results indicate that a fair degree of purity may be expected within the next five or six years. Selfing in many hybrids has, owing to non-viability of pollen, been impossible, and where the plants have shown exceptionally good morphological characters cross-pollination has been resorted to, selected Kent *arabica* plants being used as the male parent. Our final aim must, of course, be to use homozygous material for crossing, but if we were to wait for this we should have to postpone all hybridization work for many years. It is expected that by using the large masses of admittedly heterozygous material now available on the Station, valuable strains of coffee will be obtained within a period of not more than ten years. Our main object is, while retaining the high quality for which South Indian coffee is so well known, to develop high-yielding strains that will be much more vigorous and resistant to disease than those at present being grown.

A beginning has been made on the study of the inheritance of resistance to leaf-disease, which is so marked among many of the *liberica-arabica*

crosses on the selection-plots of the Station. As already mentioned, the study of this disease led to the discovery of two distinct physiological strains of *Hemileia vastatrix* with which laboratory inoculation experiments on detached coffee-leaves were commenced. Working with the individual strains, a number of tests for susceptibility and resistance has been made on the parents and F_1 generation of some of the selections made at the Station. This work has not as yet proceeded very far, but the initial results indicate that disease-resistance is inherited along relatively simple Mendelian lines, with resistance dominant to susceptibility. It also appears that the factors of resistance to each strain of *Hemileia* are distinct, though probably not entirely independent. In one family there is strong evidence that resistance to strain No. 1 is inherited as a single factor.

This work is only in its early stages, but it holds out considerable promise for the future.

Experiments on grafting have been in progress for the past four years. A very large amount of valuable information has been collected which it is proposed to publish at an early date. Grafting has been successfully carried out through eight months of the year both in the nursery and in the field. *Robusta* seedlings have been used mainly as stock, and the scions have come from *arabica* trees selected for vigour and high yield. More recently we have used as stock, seedlings of the vigorous Netrakonda hybrid.

One of the main functions of field grafting would seem to be the establishment of selected *arabica* material on vigorous root-stocks in parts of estates where the growth of *arabica* plants is normally unsatisfactory. The results so far obtained in this connexion are full of promise.

The replacement on estates of poor yielding but vigorous plants by stumping and then grafting scions from high-yielding plants on to developing suckers, has also been undertaken. This appears to be a most promising method of improving the population of coffee estates, but it will still be some years before definite results are available.

Another important function of coffee-grafting is multiplication of promising breeding-material. It is a general rule on the Station to multiply promising material in this way so that, should the parent tree die for any reason, it will not be lost.

It is fully realized that the use of seedling-stocks derived from heterozygous plants must result in variations in the grafted product. Following the work at East Malling, experiments have been started on the vegetative reproduction of stocks, and the preliminary results are promising.

It is a matter for most profound regret that this essential scientific work for the improvement of the South Indian coffee industry was not started many years ago. As a matter of fact, I prepared plans for a Coffee Experiment Station as long ago as 1913, but the funds that were then set apart for this project had, in the view of the Mysore Government of that time, to be devoted to other purposes. It is, however, a matter of most profound gratification to me that now, when I am breaking a connexion of more than a quarter of a century with agricultural development work in India, I am able to leave behind me a well-organized, if

small, Coffee Experiment Station, which I believe will play an important role in restoring the South Indian coffee industry to its former position of importance.

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THE BORDER EFFECT IN PLOT EXPERIMENTS

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Introduction

In field experiments, particularly manurial trials, the influence of the more favourable treatments on the edge rows of those less favourable has long been apparent. But not much importance has been attached to it in the past, for the plots were comparatively large and square in shape, so that the edge rows only accounted for a small fraction of the area of the plot, and hence there was little cause for discarding them. Although there may have been border effects, the ratio the edge rows bore to the plot was so small that the results would show little or no appreciable difference whether the edge rows were discarded or not. However, since the introduction of the narrow-and-small-plot methods of experimentation, in which discarding the edge rows may sometimes mean rejecting almost half the material, there has been a temptation to include the edge rows. To the practical field experimenter, whose chief anxiety is to keep the standard error as low as possible, discarding may appear not only a waste of good material, but detrimental to the efficiency of the experiment. It also involves extra labour at harvest.

The object of this paper is to illustrate the inadvisability of including the edge rows in variety trials and cultivation experiments with narrow or very small plots. It will be shown that the rejection of the edge rows in these experiments has no deleterious effects on the efficiency of the experiments, and that there are border effects attributable to competition and to the trespassing of the treatments, which, when the entire plot is harvested, may result in a considerably biased estimation of the treatment differences.

In manurial trials the rejection of edge rows involves a further factor, since the relative yields of edge rows and centre rows will be affected by any uneven distribution of the manures. The advisability of rejecting edge rows is thus considerably more doubtful, and it appears that special precautions should be taken in experiments with small or narrow plots to ensure that the edge rows receive their proper share of the manures.

Material

The only available data for this study were those from four experiments: a manurial experiment with kale conducted at Woburn Experimental Station, a cultivation and thinning experiment with kale conducted at Rothamsted, and two sugar-beet experiments (one spacing and manurial, and one manurial) also conducted at Rothamsted. In Expt. I the weight of each row was recorded separately. In Expt. II each plant was weighed separately. In Expt. III the two edge rows were weighed together. In Expt. IV the edge rows and end plants of the other rows

were weighed together. In the two sugar-beet experiments only the roots have been considered in this study. A summary of the main treatment yields with and without the rejection of the edge rows, and other particulars of each experiment are given in Tables 2. In Expts. II and IV the edge rows and end plants of the other rows have been discarded, and in Expts. I and III the edge rows only have been rejected. The area of the plots with and without the rejection of the edge rows, the number of rows, and the ratio the edge rows bear to the plots are given in Table 1.

TABLE 1

Experiment	*I*	*II*	*III*	*IV*
Area without rejection (acres) .	0·025	0·0046	0·018	0·0040
Area with rejection (acres) . .	0·015	0·0025	0·014*	0·0029
Number of rows per plot . .	5	5	8*	12
Approximate fraction of plot discarded	$\frac{2}{5}$	$\frac{1}{2}$	$\frac{1}{4}$*	$\frac{2}{7}$

* Where rows are spaced 15 in. apart.

The dimensions of the plots are: Expt. I, 109 ft. rows × 10 ft.; Expt. II, 20 ft. rows × 10 ft.; Expt. III, 80 ft. rows × 10 ft.; and Expt. IV, 11 ft. 8 in. rows × 15 ft.

TABLE 2. *Summaries: Edge Rows rejected and included*

Experiment I. Marrow-stem Kale, Rothamsted, 1932.

System of replication: 6 randomized blocks of 4 plots each.

Treatments: Unthinned; Thinned to 18 in., in combination with ordinary cultivation (June 2–4, horse-hoe); intensive cultivation (June 2–4, horse-hoe, July 4, 19, 27, motor-hoe).

Basal manuring, per acre: 16 tons dung, 2 cwt. sulphate of ammonia, 3 cwt. superphosphate, and 3 cwt. 30 per cent. potash manure salt.

Green Material

	Unthinned		*Thinned*		*Mean*	
Tons per acre	*Rejected*	*Included*	*Rejected*	*Included*	*Rejected*	*Included*
Ordinary cultivation .	27·65	28·02	25·18	23·90	26·42	25·96
Intensive cultivation .	25·51	27·92	23·63	23·54	24·57	25·73
Mean . .	26·58	27·97	24·40	23·72	25·50	25·84

Standard errors: 0·323 tons (rejected), 0·366 tons (included).

Experiment II. Marrow-stem Kale, Woburn, 1932.

System of replication: 8×8 Latin square.

Basal manures (plots receiving no dung): 0·5 cwt. P_2O_5 per acre as superphosphate, and 30 per cent. potash manure salts at the rate of 1 cwt. K_2O per acre.

Green Material

	No S/Amm.		*S/Amm. 0·2 cwt. N*		*S/Amm. 0·4 cwt. N*		*S/Amm. 0·8 cwt. N*		*Mean*	
Tons per acre	*Rejected*	*Included*	*Rejected*	*Included*	*Rejected*	*Included*	*Rejected*	*Included*	*Rejected*	*Included*
No dung	12·58	13·29	17·64	17·76	20·35	19·67	26·15	24·36	19·18	18·77
Dung 15 tons	20·28	19·19	22·87	21·24	24·58	23·67	30·56	28·74	24·57	23·21
Mean	16·43	16·24	20·26	19·50	22·46	21·67	28·36	26·55	21·88	20·99

Standard errors: 0·863 tons (rejected), 0·713 tons (included).

Experiment III. Sugar-beet, Rothamsted, 1933.

System of replication: 12 randomized blocks of 6 plots each.

Certain degrees of freedom representing interactions are confounded with block differences. Absolute replication if fourfold.

Treatments: 0·0, 0·3, 0·6 cwt. N per acre given as sulphate of ammonia in combination with rows spaced 10, 15, 20 in. apart.

Basal minerals: (0·5 cwt. P_2O_5 per acre as superphosphate, 1 cwt. K_2O per acre as 30 per cent. potash manure salt) ploughed under and harrowed in.

Roots (washed)

Mean of all levels of N

Tons per acre *Edge Rows*	*Rows spaced 10 in. apart*		*Rows spaced 15 in. apart*		*Rows spaced 20 in. apart*		*Mean*	
	Rejected	*Included*	*Rejected*	*Included*	*Rejected*	*Included*	*Rejected*	*Included*
Basal minerals ploughed in	8·12	8·05	7·04	6·93	5·77	5·73	6·98	6·90
Basal minerals harrowed in	7·22	7·28	6·07	5·99	4·99	4·98	6·09	6·08
Mean	7·67	7·66	6·56	6·46	5·38	5·36	6·54	6·49

Standard errors: 0·14 tons (rejected), 0·13 tons (included).

Experiment IV. Sugar-beet, Rothamsted, 1933.

System of replication: 3 randomized blocks of 16 plots each.

Treatments: (1) 0·0 and 0·6 cwt. N per acre as sulphate of ammonia applied on the surface; (2) No PK, PK applied in the surface soil, PK applied in subsoil, PK applied in surface and subsoil (double dressing); (P = 0·5 cwt. P_2O_5 per acre as superphosphate. K = 1·0 cwt. K_2O per acre as 30 per cent. potash manure salt); (3) No dung, 20 tons dung, applied in surface soil, subsoil, and in surface and subsoil (double dressing).

Roots (washed)

Tons per acre		*No PK or dung*	*PK only*			*PK and dung*			
			Shallow	*Deep*	*Shallow and deep*	*Shallow*	*Deep*	*Shallow and deep*	*Mean*
Edge rows rejected	No N	4·82	4·99	6·37	6·50	7·88	7·74	8·06	6·62
	N	4·76	5·43	6·64	6·68	7·52	7·30	9·00	6·76
	Mean	4·79	5·21	6·51	6·59	7·70	7·52	8·53	6·69
Edge rows included	No N	4·85	4·80	6·04	6·29	7·57	7·57	7·41	6·36
	N	4·81	5·34	6·46	6·55	7·15	6·96	8·46	6·53
	Mean	4·83	5·07	6·25	6·42	7·36	7·26	7·93	6·45

Standard errors: 0·650 tons (rejected), 0·650 tons (included).

Standard Errors

The two main sources of error in plot experiments are variations due to soil heterogeneity and variations due to the genetical composition of the plant. As we reduce the size of the plot we should reduce the error due to broad irregularities of soil, but as the number of plants is reduced the error due to plant variation and local soil irregularities is liable to be increased. Variations in the edge rows due to the trespassing of the treatments or to similar causes will be an additional source of error, and provided there are sufficient plants, discarding the edge rows may increase the efficiency of the experiment.

Each experiment has been analysed by the procedure of the analysis of variance, both with the edge rows rejected and with the edge rows included, and the standard errors have been calculated in each case. The standard errors are given in Table 3. In general the rejection of the edge rows has made practically no difference to the standard errors. In Expt. I the rejection of the edge rows has reduced the standard error per plot from 3·52 per cent. to 3·10 per cent. Even in Expt. II, in which the rejection of the edge rows and end plants of the other rows has reduced the number of plants from 100 to 54, the standard error has shown only a slight increase.

It may be concluded that, in general, discarding the edge rows will have no deleterious effects on the efficiency of the experiment, and that in certain instances a reduction in the standard error is to be expected.

TABLE 3

	Percentage standard error per plot				*No. of plants per plot*			
Experiment	*I*	*II*	*III*	*IV*	*I*	*II*	*III*	*IV*
Edge rows included .	3·52	9·60	7·21	17·70	360*	100	760†	168
Edge rows rejected .	3·10	11·16	7·65	17·53	216*	54	570†	120

* Where plots are thinned. † Where rows are spaced 15 in. apart.

Bias

In field experiments where the size and shape of the plots are such that the edge rows and edge plants comprise a comparatively large proportion of the plot area, any edge-row effects will make an appreciable difference between the estimation of the yield from the entire plot and that from the plot with the edge rows rejected. For example, the edge-row effect may have been due to the trespassing of the treatments, so that the edge rows of the untreated plots may have benefited by being adjacent to the treated plots. The estimated yield from the untreated plots with the edge rows included will be higher than that from the plots with the edge rows discarded. Thus the increase in yield due to the application of the favourable treatment will be less in the former case than in the latter. It will therefore be apparent that the more unbiased

estimate of the treatment yields will be that from the plots with the edge rows discarded, for there will be a bias in favour of the untreated plots and against the treated plots when the entire plot is harvested.

Both positive and negative biases are possible. They may arise in several ways.

Bias due to plant competition.—In thinning and spacing experiments the edge rows of the favourably treated plots when adjacent to the unfavourably treated plots are likely to produce higher yields than the central rows, and the edge rows of the unfavourably treated plots lower yields than their inside rows. The bias of the thinning effect in Expt. I is a striking example of the magnitude such competition effects may attain.

Bias due to cultivation.—When two adjoining plots each receive different 'after seeding' cultural treatments, the problem always arises as to what cultivation the space between the edge rows should receive. Is it to receive one or other of the cultivations? Or is it to be left uncultivated? Whatever treatment it receives, the yields of the edge rows are liable to differ from those of the central rows. This is illustrated in the cultivation treatment of Expt. I, where there was actually a statistically significant (but inexplicable) reversal of cultivation effects on the edge rows.

Bias due to manurial treatments.—This bias will be due primarily to the trespassing of roots and manures. The trespassing of manures may occur in two ways. There may be the actual surface straying of the manures due to their inaccurate application. This is more likely to occur with artificial fertilizers than with farm-yard manure, for any straying in the application of the latter will be visible and the particles that have strayed can easily be removed. The other form of trespassing is the lateral spreading of the manures under the surface of the soil, because all the manure will not permeate into the soil in a strictly vertical direction; although the manures may have been applied with great care and accuracy, there will still be a trespassing of the manures on to the adjoining plot. This trespassing will be greater at the lower depths of the soil. Thus it should be more apparent with deep-rooted than with shallow-rooted plants.

Bias due to uneven fertilizer-distribution.—To obtain even distribution of manures in small-scale experiments, the experimenter usually relies entirely on the skill of the man applying them. If the edges of the plot are over- or under-dosed, the amount applied to the insides of the plot will be respectively less or more. In such cases the rejection of edge rows may give more biased results then their retention. Distribution errors of this type may be expected to reveal themselves by producing consistently lower (or higher) yields on the edge rows of the manured plots with little or no difference on the unmanured plots. Unfortunately, however, there are other causes, e.g. excessive trampling, which tend to lower the yields of the edge rows, and such effects in combination with the trespassing effects already discussed will produce very similar results to those that would be obtained by giving an undue share of the manures to the centre of the plot.

That there are considerable differences between the apparent responses

to treatments according as the edge rows are included or excluded, will be seen from Table 4, where the difference between the increase in yield from the plots with the edge rows discarded and that from the plots with the edge rows included is expressed as a percentage of the increase in yield from the former. For example, in Expt. I the difference between the increases due not to thinning is 2·07 tons, which when expressed as a percentage of 2·18 tons gives a difference of 95 per cent. For non-manurial treatments these percentage differences may be regarded as estimates of the bias caused by the retention of the edge rows.

The results of Expts. II and IV given in Table 2 suggest that there was some unequal spreading of the manures in addition to trespassing. This point is examined in more detail in the next section.

TABLE 4

Experiment	*Treatment*	*Increase with edge rows discarded*	*Increase with edge rows included*	*Percentage difference*
		Tons per acre		
I. Kale	Unthinned *v.* thinned	2·18	4·25	+95
	Ordinary cultivation *v.* intensive cultivation	1·85	0·23	−88
II. Kale	0·8 cwt. N as S/A *v.* no N	11·93	10·31	−14
	15 tons dung *v.* no dung	5·39	4·44	−18
III. Sugar-beet (roots)	Basal minerals ploughed under *v.* basal minerals harrowed in	0·89	0·82	−8
	Rows spaced 10 in. apart *v.* rows spaced 20 in. apart	2·29	2·30	0
IV. Sugar-beet (roots)	2 units PK *v.* no PK	1·79	1·60	−11
	40 tons dung *v.* no dung	1·95	1·51	−23

Note. The increase is in favour of the first-mentioned treatment in each case.

Estimation of the Magnitude of the Edge Effects

The bias introduced into a treatment difference does not give a direct estimation of the trespassing or competition effect, since the magnitude of the bias depends also on the actual experimental arrangement, and the size and shape of the plots. A direct and much more accurate estimate can be obtained by utilizing the yields of the individual edge rows.

If an edge row of a plot receiving treatment A is contiguous to a plot receiving treatment B, and t_a and t_b represent the increase (per row) produced by treatments A and B when there is no edge effect, the yield of the edge row may be expected to be increased by an amount

$$\lambda t_a + \mu t_b,$$

where $\lambda+\mu = 1$. Assuming for the moment that t_a and t_b are known and their difference is δt, the difference between the yield of the edge row, y_e, and the mean yield of the central rows, y_c, may be expected to be given by

$$\begin{aligned} y_e - y_c &= (\lambda t_a + \mu t_b) - t_a \\ &= \mu(t_b - t_a) \\ &= \mu\delta t, \end{aligned}$$

subject to errors of various types. In this equation the effect of any fertility or other difference affecting the whole of the plot is eliminated. There will be one such equation for every edge row except those at the edges of the experimental area.

If each plot is subjected simultaneously to two different treatments, as in a complex experiment, and the effects of these treatments are assumed to be additive, the equation will become

$$y_e - y_c = \mu_1 \delta t_1 + \mu_2 \delta t_2.$$

When both edge rows of the plot are weighed together, as happened in Expt. III, the appropriate equations for the two edge rows separately must be combined into a single equation of the type

$$y_e + y'_e - 2y_c = \mu_1(\delta t_1 + \delta t'_1) + \mu_2(\delta t_2 + \delta t'_2).$$

Estimates of the values of the edge-effect coefficients μ_1 and μ_2 may be made by the method of least squares, i.e. the method ordinarily used for partial regressions and fitted constants.

The procedure will be approximate in two respects. First, we do not know the true values of the treatment differences, and estimates of them must be made from the experimental results (using the yields with the edge rows rejected). If the soil fertility varies continuously, it is not difficult to see that this will tend to exaggerate (in a positive direction) the values of μ obtained. If, however, the treatment effects are large compared with their standard errors, and the experiment is also large, so that the average treatment differences are well determined, this disturbance should not be great, but clearly it would be inadvisable to attempt to take into account the interactions between the different types of treatment.

The second source of disturbance is due to the fact that the same centre rows occur in two equations (one for each edge row of the plot), and the errors will therefore not be wholly independent. This will tend to exaggerate the significance of the results when tested in the ordinary manner. It could be avoided by combining the two equations for each plot into one (as was necessarily done in Expt. III, where both the edge rows were weighed together) but this would sacrifice a considerable part of the available information. Alternatively differences of each edge row with the next neighbouring row might have been taken, but even here some correlation is likely to remain, and the errors would probably be larger.

The possibility of unequal distribution of the manures, and the effects of trampling, &c., on the edge rows, remain to be considered. As far as trampling is concerned it will be reasonable to assume that the yields of the edge rows are diminished by a constant amount. Unequal distribution may be represented as follows. If the true density of the manures per unit area is ρ, and the density on the edge rows is $\rho(1-\lambda)$, the density on the centre rows of, say, a five-row experiment will be $\rho(1+\frac{2}{3}\lambda)$, and therefore the difference in yield between the edge rows and the centre rows may be expected to be

$$-\tfrac{5}{3}\lambda t,$$

where the response (assumed linear) to the correct dressing is t and spreading and competition effects are neglected.

Expts. II and IV are the only experiments involving direct responses to manures. Expt. IV, however, was not very suitable for the application of the method, as the whole of the edge of each plot was weighed together. Expt. II, when analysed by this method, gave some rather surprising results. Using a regression equation of the type

$$y_e - y_c = c + \mu_N \delta t_N + \mu_D \delta t_D - \tfrac{5}{3}\lambda_N t_N - \tfrac{5}{3}\lambda_D t_D,$$

where N indicates sulphate of ammonia, and D dung, the following values for the coefficients were obtained.

$$\begin{aligned} c &= -0{\cdot}71854 \pm 1{\cdot}552 \\ \mu_N &= +0{\cdot}11176 \pm 0{\cdot}077 \\ \mu_D &= -0{\cdot}18940 \pm 0{\cdot}119 \\ \lambda_N &= +0{\cdot}06300 \pm 0{\cdot}075 \\ \lambda_D &= +0{\cdot}24121 \pm 0{\cdot}111 \end{aligned}$$

Only λ_D is significant, but its actual value appears to be unduly high. It is scarcely likely that the edge rows of the dunged plots received only about three-quarters of their true dressing; on the other hand λ_N and λ_D are not significantly different, and their mean value, 0·15, indicating about five-sixths of the proper dressing on the edge rows, is not unreasonable.

Though neither of the coefficients of trespassing μ_N and μ_D is significant, the negative value of μ_D is in itself a little surprising. It may be that this is a competition effect, but some fortuitous interaction between μ_D and λ_D may possibly account for these anomalies; for instance if λ_D were assumed equal to 0·1, this would automatically reduce μ_D considerably.

In Expt. II, therefore, it appears that the main cause of the observed bias is the unequal distribution of the manures. It should be remembered, however, that the effects of trespassing and unequal distribution are somewhat similar (especially when as here a constant term c is included in the regression equation), and it would be unwise to conclude on the evidence of this experiment alone that trespassing effects of manures are necessarily always negligible.

Expt. I, in which there are no manurial treatments, shows very striking edge effects. A slightly different form of equation was used for the reason that the space between intensively cultivated and ordinarily cultivated plots was given ordinary cultivation. The equation for the edge row of the intensively cultivated plot must therefore contain a μ for cultivation effect, whilst the equation for the edge row of the ordinarily cultivated plot will contain no μ for cultivation effect, since both sides of this row receive ordinary cultivation. The expected value of this μ will be 0·5. The calculated value, $+0{\cdot}95 \pm 0{\cdot}637$, is considerably, but not significantly, greater.

The thinning in this experiment shows a very remarkable competition effect, the outside rows of the unthinned plots growing exceptionally well owing to the reduction of competition from their thinned neighbours, which in their turn were unduly depressed. The value of μ, $-1{\cdot}58$

$\pm 0{\cdot}308$, indicates that the difference between the thinned and unthinned edge rows was no less than four times the difference between the thinned and unthinned central rows.

In Expt. III it is not possible to consider inequalities of distribution, since there are no plots without basal manures, and therefore their effect is unknown. Nitrogen showed no effects and was therefore omitted. The value of μ for 'basals', $+0{\cdot}24 \pm 0{\cdot}121$, is significant. The value of μ for spacing, $+0{\cdot}14 \pm 0{\cdot}064$, is also significant, and not quite significantly different from the value of $0{\cdot}25$, which would be expected if there were no competition effects.

In only one of the three experiments did the value of c approach significance, thus indicating that the edge rows did not suffer greatly from extra treading, &c.

Summary

1. The results of four experiments in which the edge rows were harvested separately were examined in order to determine the importance or otherwise of rejecting edge rows in experiments having small or narrow plots.

2. It was found that the rejection of edge rows did not appreciably increase the standard errors of the experiments.

3. It is shown that in experiments where the plots are narrow or very small, the retention of the edge rows will give decidedly biased estimates of the treatment differences, due to the trespassing and competition effects of the treatments on the edge rows. It is also shown that in manurial experiments the discarding of edge rows may give more biased results than their retention, due to the unequal distribution of the manures between the centres and outsides of the plots.

In conclusion, I wish to acknowledge my indebtedness to Mr. F. Yates, Head of the Statistical Department, Rothamsted, under whose guidance this work has been carried out.

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THE RESPONSE OF GRASSES AND CLOVER TO TREATMENT ON ACIDIC UPLAND SOILS, AND THE EFFECT OF HERBAGE PLANTS ON THE REACTION OF ACIDIC SOILS

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PART I. The response of herbage plants to treatment on *Molinia* soil.

INVESTIGATIONS carried out by the Welsh Plant Breeding Station within recent years demonstrate the potential value of the acidic upland soils of Wales. They show that, provided the serious mineral deficiencies in these soils are rectified, a phenomenal increase in herbage production is forthcoming [1]. Further, the herbage thus obtained is definitely superior in nutritive value, being richer in nitrogen and in ash constituents [2].

It is becoming increasingly evident that these upland areas present problems of exceptional interest both from a biochemical and an agronomical standpoint. On the one hand, there are many factors still to be explored that govern the rate of decomposition of the large reserve supplies of carbon and nitrogen in these soils. On the other hand, there is the question of the most suitable herbage plants and their management for the conversion of these nutrient supplies into food.

As the fertility-level to which these acidic soils can be raised depends on the harmonizing of a number of diverse factors, an experiment was designed to study their response, not only to a single treatment, such as manuring, but also to a combination of treatments, including the introduction of cultivated grasses and wild white clover.

This experiment was initiated in 1931 on both the *Molinia* and fescue soils of the Plynlymon area. In the following section the results obtained over a period of three years from the more acidic of these two soils, viz. the *Molinia* soil, will be presented. This *Molinia* soil on which the experiment was conducted stands on a heavy stratum of clay, and in an exposed situation. A large quantity of stones and fine gravel is intermingled with the clay of the lower horizons, but owing to the comparatively low percentage of organic matter in these horizons the clay has a binding effect, and drainage from the surface layer is seriously retarded.

The following table indicates the mechanical composition of the various horizons, and their pH values as determined with the quinhydrone-electrode.

It is seen that the fraction at a depth of a foot below the surface contains an exceptionally high percentage of clay. The highest acidity is obtained in the surface soil, and this diminishes on passing into lower layers, being generally related to the organic matter present.

TABLE 1. *Mechanical Composition and Acidity of Soil in* Molinia *Area.* (*Constituents expressed as percentages of material passing through a 1 mm. sieve*)

Depth of sample	*Stone and fine gravel*	*Coarse sand*	*Fine sand*	*Silt*	*Fine silt*	*Clay*	*Moisture*	*Loss on ignition*	*pH*
0 – 5½ in.	24·0	1·59	3·43	19·00	20·12	10·06	5·28	37·71	3·76
9½–12½ in.	61·1	5·66	16·38	13·60	32·40	16·06	2·84	13·07	4·35
12½–21½ in.	655·0	27·86	6·54	11·75	17·75	19·06	4·40	12·57	4·54
21½–26½ in.	176·5	29·32	4·77	15·07	25·31	15·56	2·15	7·41	5·13

Experimental. The experiment consisted in giving 20 different treatments to the soil. Each treatment was triplicated, so that the strip of land used was divided into 60 small plots, each plot being 4 sq. yd. in area. The treatments are shown in Table 2 (p. 326). An attempt was made to keep the plots receiving identical treatment at a good distance apart, so as in some measure to eliminate the great variations in soil conditions which characterize the area. All the plots, except T, R, I, G, received thorough manual cultivation down to a depth of 5–8 in. This cultivation consisted in chopping the hard surface-mat as finely as possible, and incorporating it with the surface-soil by means of spades and large edging-tools. After receiving various manurial treatments at the end of April 1931, all the cultivated plots, except G, H, and Q, were sown with a mixture containing equal weights of indigenous strains of perennial rye-grass, cocksfoot, and wild white clover at a rate equivalent to 40 lb. per acre. No sowing was made in Q, and clover was omitted from the mixture sown in G and H. The experimental plots were fenced off from the surrounding land, and separated one from the other by suitable spaces and paths.

Where basic slag (15 per cent. P_2O_5) was applied, it was distributed at a rate equivalent to 12 cwt. per acre. Such a liberal dressing ensured an adequate supply of phosphate in the soil for some years, in spite of the heavy leaching of phosphate which is known to occur from the acidic upland soils of Wales [3]. Sulphate of potash (54 per cent. K_2O), where used, was always applied at a rate equivalent to 1½ cwt. per acre. Limestone and nitro-chalk were applied in varying quantities as indicated below. All the manures, including limestone and nitro-chalk, were applied in a very fine state of division, previous experiments having shown the importance of this [4]. Where limestone and nitro-chalk were used in conjunction with one another, they were thoroughly incorporated before being applied. The treatments can, for the sake of convenience, be divided into three groups, viz. the treatment of the uncultivated plots, the treatment of cultivated plots where artificial nitrogen was included, and the treatment of the cultivated plots where artificial nitrogen was not used.

Single-treatment Effect compared with the Cumulative Effect of Combined Treatment

Two cuts were taken from each plot during 1931, and three cuts during each of the seasons 1932, 1933, making a total of 1,440 cuts from

TABLE 2. *Manurial Treatments*

Plots	*Seeding*	*Manurial treatment (per acre) at commencement*	*Subsequent treatment (per acre)*
	Group 1—Uncultivated plots		
T	Nil	Nil	Nil
R	,,	12 cwt. basic slag + 8 cwt. nitro-chalk	,,
I	,,	12 cwt. basic slag + 1½ cwt. sulphate of potash + 1 ton limestone + 8 cwt. nitro-chalk	1½ cwt. nitro-chalk applied June 1931 and ½ cwt. ferrous sulphate applied August 1931
J	,,	As I, but including 3 tons soil from clover field	As I
	Group 2—Cultivated plots given artificial nitrogen		
O	Complete mixture	8 cwt. nitro-chalk	Nil
E	,, ,,	12 cwt. basic slag + 1½ cwt. sulphate of potash + 1 ton limestone + ¾ cwt. nitro-chalk	,,
F	,, ,,	As E, but with 3 tons clover field soil	,,
G	Grasses without clover	12 cwt. basic slag + 1½ cwt. sulphate of potash + 1 ton limestone + 1½ cwt. nitro-chalk	1½ cwt. nitro-chalk applied June 1931 and ½ cwt. ferrous sulphate applied August 1931
H	,, ,,	As G, but with 3 tons clover field soil	As G
L	Complete mixture	12 cwt. basic slag + 8 cwt. nitro-chalk	Nil
Q	Nil	As L	,,
M	Complete mixture	2 tons farmyard manure + 8 cwt. nitro-chalk	,,
N	,, ,,	10 cwt. sewage sludge + 8 cwt. nitro-chalk	,,
	Group 3—Cultivated plots where artificial nitrogen was not used		
K	Complete mixture	Nil	Nil
S	,, ,,	Farmyard manure	,,
P	,, ,,	12 cwt. basic slag	,,
A	,, ,,	,, ,, + ½ ton limestone	,,
B	,, ,,	,, ,, + ¾ ton limestone	,,
C	,, ,,	,, ,, + 1 ton limestone	,,
D	,, ,,	,, ,, + 1½ cwt. sulphate of potash + 1 ton limestone	,,

the whole *Molinia* area. These were taken at intervals of about two months during the growing period, each series of cuts being dried, weighed, and analysed chemically. One series of the natural-herbage plots, which served as controls, received no treatment other than this lenient cutting. A second series was manured only; a third cultivated only; whilst a fourth was cultivated in addition to receiving the same manurial treatment as the second. A comparison of the yields of dry matter resulting from these single and combined treatments is given in Table 3, together with the rainfall during each growing season.

TABLE 3. *The Effect of Single and Combined Treatments on the Yield of Dry Matter from the Herbage of the* Molinia *Area*

Season	*Yield in grams of dry matter per plot*			*Relative yields with control at 100*		
	1931	*1932*	*1933*	*1931*	*1932*	*1933*
Control (T)	720	668	124	100	100	100
Manuring only (R)	984	863	318	137	129	257
Cultivation only (K)	23	331	335	3	49	270
Manuring + cultivation (Q)	197	1,021	581	27	153	469
Rainfall (April–September)	26·22 in.	19·96 in.	9·87 in.			

In 1931, the first cut taken on those plots which had not been cultivated included some old vegetation which had developed before the

manures were applied, and the effect of which was to diminish the concentration of nitrogen and to increase the dry matter. This would explain why the yield of dry matter in the first year was greater than that in the second. Owing to the abnormally low rainfall during the third season, the yield from all plots was much lower than would have been obtained in a normal year. It is evident that the effect of the inadequate water-supply in curtailing yield during 1933 has been lessened as a result of the various treatments, and especially as a result of combined manuring and cultivation. On the control plots we find that the yielded during 1933 is only 19 per cent. of that obtained during 1932, but on the manured plots the yield is 37 per cent. of the satisfactory yield obtained on them in the previous season. Where both manuring and cultivation have been adopted the yield during 1933 is 58 per cent. of a still more satisfactory yield resulting from this combined treatment in 1932. It should be emphasized that these effects mitigating the harmful influence of extremely dry weather were obtained during the third season after the actual operations of manuring and cultivating. There is no doubt that cultivation has had as sustained and profound an effect on the resistance to drought as manuring. We find that the cultivated plots yield as much herbage during 1933 as during 1932. Cultivation alone, however, is of no avail, owing to the low, if consistent, yield which such a treatment affords. Where the serious effects of dry weather have to be countered, the combined action of manures and cultivation scores heavily over either of these treatments taken alone. Since the insurance value of any treatment against unusual climatic conditions is of equal importance to its capacity to give immediate response, it is of special interest to find that the insurance provided by the combined treatment of manuring and cultivation on this *Molinia* area at the end of the third season is a substantial one.

Table 4 shows the effect of these single and combined treatments on the nitrogen, lime, and phosphate of the herbage.

TABLE 4. *The Effect of Single and Combined Treatments on the Chemical Composition of the Herbage in the* Molinia *Area.* (*Percentages based on dry matter; seasons 1931–3*)

	Nitrogen			*Lime*			*Phosphate*		
	Max.	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*
Control (T)	2·00	1·63	1·78	0·466	0·371	0·416	0·313	0·215	0·264
Manuring only (R) . . .	2·01	1·67	1·83	0·616	0·462	0·521	0·418	0·375	0·446
Cultivation only (K) . .	2·26	1·70	2·19	0·485	0·377	0·432	0·348	0·244	0·304
Manuring + cultivation (Q) .	2·12	1·94	2·03	0·663	0·601	0·626	0·636	0·497	0·556

The mean value given in Table 4 for the concentration of the various chemical constituents is the true mean for the produce of the three seasons under review, taking into consideration the relative yields obtained from the different cuts. The maximum and minimum concentrations are those obtained for the total produce of one season's growth. It will be noted that an exceptionally low concentration of lime and phosphate remained as an outstanding feature of the control plots throughout

the experimental period. In the single treatments cultivation had little influence on the mean concentration of ash constituents, but had a decided effect in increasing that of nitrogen; and manuring alone notably increased the lime and phosphate concentrations. The combined manuring and cultivation was, however, more effective in raising the concentration of ash constituents, and particularly that of the phosphate, than either of the single treatments.

In a good pasture the phosphate concentration is either practically the same as, or more often greater than, that of the lime concentration [5]. Under the system of cutting adopted in this experiment, the phosphate concentration of these mountain pastures is lower than that of the lime, the lime-phosphate ratio being 1·58. The combined treatment of manuring and cultivation is significant not only because it increases the contents of lime and phosphate, but also because it alters the lime-phosphate ratio from 1·58 to 1·13. The optimum ratio for any given pasture from the nutritional standpoint would depend not only on the availability of the lime and phosphate themselves, but also on the nature and amount of other constituents present, particularly the other basic and acidic radicles. Considering, however, that wild white clover, which plays such a dominant part in the improvement of these upland areas, markedly increases the ratio of lime to phosphate, it is reasonable to suppose that a treatment which increases the phosphate concentration to a greater extent than the lime, tends to bring about a more satisfactory balance between the mineral constituents of the herbage.

TABLE 5. *The Relative Yields of Chemical Constituents for Single and Combined Treatments.* (*Control plots at 100*)

	Nitrogen			*Lime*			*Phosphate*		
	1931	*1932*	*1933*	*1931*	*1932*	*1933*	*1931*	*1932*	*1933*
Control (T)	100	100	100	100	100	100	100	100	100
Manuring only (R)	143	137	241	136	193	414	238	221	406
Cultivation only (K)	3	62	288	3	50	348	4	41	351
Manuring + cultivation (Q)	36	157	455	38	248	819	81	282	881

Table 5 shows that although the manured plots have given a heavier yield of constituents than the cultivated plots during the first two seasons, during the third season there is no great difference between the yield of constituents from these two treatments applied singly. During the second and third seasons the combined treatment is superior to either of the single ones. This superiority is most strikingly brought out in the yield of chemical constituents during the season of 1933 when the dry weather profoundly affected production, particularly on the untreated plots.

The Establishment of the Sown Species

The germination of the seeds of all the three species sown was good, and a high density of seedlings per unit area resulted. The growth of the seedlings on the plots receiving both basic slag and nitro-chalk, more especially treatment L (Table 2), showed a visible superiority over that

of seedlings on the other plots in the short period of four weeks from the time of sowing (the equivalent, therefore, of two-weeks' seedling growth). In the plots receiving either basic slag or nitro-chalk alone, the growth of the seedlings was exceedingly poor, and in the second case continued to be so throughout the experiment, the plant-establishment of the sown species being negligibly small. In the slagged plots, however, growth improved later, particularly in those receiving limestone also.

At the end of the first season, the dominant plant in the plots which had not been sown with clover (G and H) was cocksfoot, and this was also true of the plots heavily manured with nitro-chalk and slag (L) in which the grasses tended to suppress the clover. Much perennial rye-grass was, however, also present and this became the dominant species during the winter (both in plots A–F and in G, H, and L). This behaviour was also shown during the second season, and owing to this continued growth of rye-grass, the plots were remarkably green during the winter, in sharp contrast to the native herbage.

In the plots receiving slag and limestone, but little or no nitrogen (plots A–F), the vegetation during the summer was dominated completely by clover. The early establishment of this plant was definitely improved by the addition to the manuring of lowland soil in which clover had formerly grown (F), but the later growth in comparative plots not inoculated (E) eliminated this superiority. The initial growth and nodulation of the plants in the uninoculated plots showed, however, that the nodule organism (*Bacillus radicicola*) is present in this soil, although clover plants are conspicuously lacking from the native herbage. The addition of limestone to the phosphate was markedly beneficial to the growth of clover and directly or indirectly to that of the grasses. In its absence, with basic slag alone given, the establishment of clover continued poor and the native grasses were dominant, with some rye-grass and cocksfoot persisting.

The remaining plots were dominated completely by the native grasses, which in the cultivated plots developed vegetatively from tillers that survived the destruction of the turf.

During the first three months after sowing, the greatest production of dry matter by the sown species occurred in the plots dominated by cocksfoot (L), but thereafter, throughout the three seasons growth, it was heaviest in the clover-dominated plots, and there can be no doubt that of the three species sown this plant was least affected by the adverse environment.

In the second summer, the dominant species in the seeded and manured plots were again cocksfoot, where excessive dressings of nitro-chalk (L) were given or clover was not sown (G and H), and clover in the rest (A–F). In the latter plots the density of cocksfoot tillers was less than where that grass was dominant, but the density of rye-grass showed no difference in the two cases, being about 35 per cent. of the total tillers present on the ground. At the beginning of the season the population of clover in the plots G, H, and L was extremely small, but by the end of the summer this species had increased so rapidly that it covered approximately 20 per cent. of the area of the plots.

By the third season, fescue and bent, derived from the surrounding native herbage, composed half the vegetation in all the plots; all the sown species, however, persisted throughout, the effect of the single manurial application lasting for at least three years. The density of cocksfoot and rye-grass in the clover plots exceeded that in those given mineral nitrogen. In those plots from which the sown species were absent and to which manures were applied, the original *Molinia* pasture changed by the third year, as a consequence of cutting, into one made up almost entirely of bent and fescue, but this did not occur in the unmanured plots (T). This phenomenon has already been described by Davies and Jones [6]. It is significant that in all the plots cultivated (i.e. those in which the original pasture was destroyed) a high proportion of bent was found.

Included in this experiment are certain plots where an attempt was made to get good grass development by manuring with slag and a heavy dressing of nitro-chalk, and where as a consequence the wild white clover was partly obliterated. There are other plots where the development of wild white clover was encouraged by the substitution of limestone for nitro-chalk. In Table 6 a comparison is made between the chemical composition of the herbage towards which clover has contributed, and that to which the clover contribution has been negligible.

TABLE 6. *The Effect of Cultivated Grasses and Wild White Clover on the Composition of Herbage in* Molinia *Area.* (*Percentages based on dry matter*)

	Nitrogen			*Lime*			*Phosphate*		
	Max.	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*
A. Manured* for grass development; cultivated; not seeded (Q)	2·12	1·94	2·03	0·663	0·601	0·626	0·636	0·497	0·556
B. Same treatment* as A; seeded with grasses and clover (L) .	2·18	2·04	2·12	0·930	0·736	0·884	0·709	0·589	0·657
C. Manured** for clover development; cultivated and seeded as in B. (C)	2·80	2·15	2·55	1·724	0·931	1·204	0·812	0·486	0·67

* 12 cwt. basic slag + 8 cwt. nitro-chalk.
** 12 cwt. basic slag + 20 cwt. limestone.

In considering these results it should be borne in mind that the first cut in each season was taken in June, and that subsequent cuts were taken at intervals of two months. Owing to the earlier maturity of the cultivated grasses (B), it follows that the natural herbage (A) compares more favourably with them in nitrogen and phosphate than it would have done if earlier and more frequent cuttings had been taken. On the other hand, owing to a relatively advanced stage of leaf-maturity, the lime-content of the cultivated grasses may be higher in relation to that of the natural herbage than it would have been under a system of more frequent cuttings [7]. It will be noted, however, that the cultivated grasses have given a higher concentration of nitrogen and phosphate than the natural herbage, in spite of the unfavourable interference of the maturity factor.

Whereas wild white clover was practically obliterated as a result of

treatment B, good clover development was obtained with treatment C. The effect of this clover is clearly reflected in both the nitrogen- and the lime-content of the herbage.

In Table 7 the effect of cultivated grasses and wild white clover on the total yield of dry matter and chemical constituents over a period of three years is shown.

TABLE 7. *Effect of Cultivated Grasses and Wild White Clover on the Total Yield of Dry Matter and Chemical Constituents. (Yield per plot, seasons 1931–3)*

	Dry matter gm.	*Nitrogen mg.*	*Lime mg.*	*Phosphate mg.*
A. Manured for grass development; cultivated; not seeded (Q)	1,799	36,673	11,247	10,466
B. Same treatment as A; seeded with grasses and clover (L)	2,274	48,228	20,121	14,949
C. Manured for clover development; cultivated and seeded as in B (C)	2,624	66,860	31,598	17,555

It is noteworthy that in treatment A the yield during the first season was smaller than in the seeded plots, since vegetative growth had not had time to occur following the destruction of the sward as a result of cultivation. When this is borne in mind, the yield of dry matter from the unsown plots over the three periods under consideration must be regarded as being very satisfactory compared with that from treatment B.

The Effect of the Application of Bacillus radicicola *on the Development of Wild White Clover*

No wild white clover is present in the natural herbage of this *Molinia* pasture, and the pH of the soil is outside the range of acidity within which white clover usually occurs [8]. On this account it was considered possible that after all the manurial requirements of the clover had been satisfied, the addition of *B. radicicola* might be a further advantage. Lowland soil in which clover had previously grown was therefore applied at the rate of 3 tons per acre to one series of plots, which at the same time received a complete manurial dressing (F). Identical treatment, except for the application of soil, was given to control plots (E). Table 8 shows the yield of dry matter and the concentrations of nitrogen and lime in the two cases.

Although the early development of the clover on the uninoculated plots showed the nodule organism to be already present in this soil, there is reason to think that it is not present in numbers at all approaching those necessary for optimum growth and nitrogen-fixation, and evidence for this belief is provided by the yields of dry matter and by the nitrogen- and lime-concentration for the first year (Table 8). In the second season from sowing, however, the growth of clover in the control plots, as represented by the yield of dry matter and by the percentage composition, is

slightly better than that in the plots receiving soil. It would seem, therefore, that the deficiency in the numbers of *B. radicicola* in the control plots has rapidly disappeared in this experiment, and that with satisfactory manurial treatment of the soil the organism multiplies at a high rate. Since, however, the initial density of the bacterium in the soil before inoculation and manuring is not known, an exact estimate of this rate cannot be made.

TABLE 8. *The Effect of applying Soil containing* Bacillus radicicola *on the Yield of Dry Matter and on the Concentrations of Lime and Nitrogen in the Produce from a Sown Mixture in Upland Soil*

	19/8/31			9/10/31			6/6/32		
Date of cutting	*Dry wt. of yield in gm. per plot*	*Percentage*		*Dry wt. of yield in gm. per plot*	*Percentage*		*Dry wt. of yield in gm. per plot*	*Percentage*	
		N	*CaO*		*N*	*CaO*		*N*	*CaO*
Control plots (E) .	310	2·49	1·72	113	3·15	1·74	608	2·58	1·73
Plots to which *B. radicicola* was applied (F) .	342	3·56	2·49	163	3·25	1·83	657	2·57	1·63

	25/7/32			30/9/32		
Date of cutting	*Dry wt. of yield in gm. per plot*	*Percentage*		*Dry wt. of yield in gm. per plot*	*Percentage*	
		N	*CaO*		*N*	*CaO*
Control plots (E) .	555	2·61	1·70	340	2·44	0·938
Plots to which *B. radicicola* was applied (F) .	465	2·60	1·39	357	2·52	1·02

In experiments on somewhat similar soil in other localities [9], the improvement of the uninoculated plots was much slower than that described above, but so many factors are different in the two cases that a comparison of the respective results is impossible.

Effect of Manurial Treatment on Yield of Dry Matter from Sown Mixture of Grasses and Clover

The principal manurial treatments adopted in this experiment included: (*a*) basic slag alone, (*b*) basic slag in conjunction with varying amounts of limestone, (*c*) basic slag and limestone with the addition of potash, (*d*) basic slag, limestone, and potash with a small quantity of nitro-chalk, (*e*) basic slag with a heavy addition of nitro-chalk. In Table 9 the effect of these different treatments on the chemical composition of the sown mixture is shown.

From the work of previous investigators on the effect of limestone on acidic soils it is evident that its effectiveness has largely depended on the circumstances under which it was applied. In the hilly districts of Wales many unsuccessful attempts have been made to improve pasture land by the application of small quantities of ground limestone. Jones and Stapledon [10], reporting on an experiment carried out to ascertain the most suitable manurial treatment for upland pastures, state that by the second year the limed plot showed practically identical results with the

TABLE 9. *The Effect of Various Manurial Treatments on the Chemical Composition of Mixture from Grasses and Clover. (Percentages based on dry matter; seasons 1931–3)*

Manurial treatment (per acre)	*Nitrogen*			*Lime*			*Phosphate*		
	Max.	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*	*Max.*	*Min.*	*Mean*
1. Nil (K)	2·26	1·70	2·18	0·485	0·377	0·432	0·348	0·244	0·299
2. 12 cwt. slag (P)	2·35	2·13	2·16	0·862	0·790	0·793	0·690	0·520	0·623
3. 12 cwt. slag + 5 cwt. limestone (A)	2·63	2·22	2·45	1·145	0·966	1·076	0·736	0·437	0·622
4. 12 cwt. slag + 10 cwt. limestone (B)	2·77	2·36	2·60	1·290	1·012	1·130	0·765	0·524	0·638
5. 12 cwt. slag + 20 cwt. limestone (C)	2·80	2·15	2·55	1·724	0·931	1·204	0·812	0·486	0·670
6. As 5 + 1½ cwt. K_2SO_4 (D)	2·69	2·13	2·49	1·670	1·173	1·296	0·783	0·473	0·634
7. As 6 + ¾ cwt. nitro-chalk (E)	2·68	2·14	2·44	1·725	1·030	1·408	0·727	0·535	0·642
8. 12 cwt. slag + 8 cwt. nitro-chalk (L)	2·18	2·04	2·12	0·930	0·736	0·884	0·709	0·589	0·657

unmanured. Ling and Wallace [11] carried out an extensive experiment on the manuring of acid pastures and found that practically no result was obtained from lime-treatment during the first two seasons and only very little during the third; but at three centres during the fourth season marked responses were recorded, and at certain others smaller responses were observed. The authors add that even after four seasons the results produced by lime are inferior to those due to basic slag and North African phosphate. Experiments carried out over a period of ten years on the cultivation of raised bog [12] indicated that the addition of lime was necessary, but that the addition might also have a harmful effect, according to the quality and form used, the kind of crop, manuring, &c.

Dawson and Evans [13] have shown that on very acid soil an application of carbonate of lime is necessary to secure a 'take' of grass-seed, and Clouston has found lime to be essential for establishing pasture on virgin peat [14].

All the treatments detailed in Table 9 were carried out in conjunction with thorough cultivation, and it is quite clear that in a soil of this type better aeration greatly enhances the efficiency of a fertilizer treatment. Another important fact to bear in mind is that in all the above treatments a seeds-mixture including wild white clover was sown. In the first series of cultivated and seeded plots (Series 1), since no manurial treatment was given, the fertility-level was too low for the development either of the cultivated grasses or of the wild white clover. Consequently, the chemical composition in this case relates to the small quantity of natural herbage that established itself on these unmanured plots.

Under the conditions of cultivation and seeding adopted in this experiment, the first fact brought out by Table 9 is that basic slag is not only a source of phosphate, but that it is also a most valuable source of lime to the plant, its effect on the lime of the herbage being as striking as its effect on the phosphate. The next fact brought out is that where small quantities of limestone ranging from 5 to 20 cwt. are applied in conjunction with slag, further marked increases in nitrogen and lime occur.

A small quantity of nitro-chalk amounting to ¾ cwt., applied in conjunction with other manures, slightly increased the lime-concentration

of the herbage, this being due to its assistance in clover-establishment.

Table 10 shows the effect of the different manurial treatments on the yield of dry matter and chemical constituents over the experimental period of three years.

TABLE 10. *The Effect of Different Manurial Treatments on the Yields of Dry Matter and Chemical Constituents from a Sown Mixture of Grasses and Wild White Clover. (Yield per plot; seasons 1931–3)*

Manurial treatment (per acre)	*Dry matter gm.*	*Nitrogen mg.*	*Lime mg.*	*Phosphate mg.*
1. Nil (K)	689	15,003	2,975	2,063
2. 12 cwt. slag (P) . . .	2,005	43,219	15,990	12,496
3. 12 cwt. slag + 5 cwt. limestone (A)	2,280	55,808	24,546	14,174
4. 12 cwt. slag + 10 cwt. limestone (B)	2,469	64,168	27,905	15,744
5. 12 cwt. slag + 20 cwt. limestone (C)	2,624	66,860	31,598	17,555
6. As 5 + 1½ cwt. K_2SO_4 (D) .	2,723	67,790	35,268	17,298
7. As 6 + ¾ cwt. nitro-chalk (E) .	2,805	68,566	39,500	18,010
8. 12 cwt. slag + 8 cwt. nitro-chalk (L)	2,274	48,228	20,121	14,949

It is evident from Table 10 that basic slag itself has profoundly affected both the yield of dry matter and that of all chemical constituents. Where limestone has been added to this foundation of phosphatic manuring, there is a still further pronounced increase in the weight of all constituents. In comparison with the influence of these two manures, the influence of both sulphate of potash and nitro-chalk has been small. A very light dressing, ¾ cwt., of nitro-chalk has undoubtedly had a favourable effect on establishment of wild white clover, but treatments (3) and (8) show that 8 cwt. of nitro-chalk has been no more effective than 5 cwt. of limestone.

The conclusion to be drawn is that the net effect of a heavy application of a nitrogenous fertilizer on these mountain areas is small where wild white clover is an important constituent of the sward. There is no doubt that on natural herbage, devoid of clover, the effect of nitrogenous fertilizers is outstanding. Previous experiments have clearly brought out their effect on such herbage, and it has been shown that on these soils of high organic-matter content the amount of nitrogen recovered in the natural herbage may be greater than that applied [15]. Where, however, wild white clover occurs in a sward on these soils, the present experiment shows that a more satisfactory yield and a better quality of produce can be obtained by the encouragement of this clover than by heavy nitrogenous manuring, which develops the grasses at the expense of the clover.

Summary and Conclusions

Experiments were commenced in the spring of 1931 to study the response of acidic upland soils to single and joint treatments, including cultivation, manuring, and the sowing of cultivated grasses and wild white clover. The results discussed in this paper are those obtained over three seasons (1931–3) on a defectively drained *Molinia* soil with a pH value of 3·76.

Twenty different treatments were given to the soil, each treatment being triplicated and carried out on small plots 4 sq. yd. in area. All the plots where seed was sown were thoroughly cultivated to a depth of 5–8 in. Some of the natural herbage plots were also well cultivated. The plots received different manurial treatments, usually just before seeding. Two cuts were taken from each plot in 1931, and three cuts in each of the seasons 1932 and 1933, the cuts being dried and chemically analysed.

The experiment was arranged to afford a comparison between the performance under various circumstances of (*a*) natural herbage, and (*b*) the produce from a sown mixture of indigenous perennial rye-grass, cocksfoot, and wild white clover.

The results show that the combined treatment of manuring and cultivation has given a dry matter richer in nitrogen, lime, and phosphate than that obtained from the natural herbage, which was manured only. This joint treatment had a pronounced effect in increasing the yield of dry matter during the third season following its application.

The sown mixture of grasses and clover has yielded more dry matter than the manured and cultivated natural herbage. If the yield of dry matter from the treated natural herbage for the three seasons be placed at 100, that derived from the grasses and clover amounts to 146.

The sown species stand in marked contrast to the improved natural herbage in respect of nitrogen- and lime-content. Whilst the nitrogen- and lime-content of the natural herbage have been improved by treatment, the concentrations are still low compared with the produce of the sown mixture.

A comparison is made between the herbage towards which wild white clover contributed and that from which wild white clover had been partly obliterated. A high protein-content was found in the clover-containing sward, whilst the clover also made a remarkable contribution towards enhancing the lime-content. A sward composed of cultivated grasses and wild white clover to which no nitrogen was applied gave a heavier yield of dry matter during the period of three years than a sward of cultivated grasses heavily manured with soluble nitrogen. It is evident that on these mountain areas wild white clover not only enhances the protein- and lime-content of the sward, but that it also makes an important contribution to its yield of dry matter.

Under the conditions of cultivation and seeding adopted, basic slag effected a marked increase in the yield of dry matter. Where limestone to the extent of 1 ton per acre was applied in conjunction with the slag, a further considerable increase in yield was obtained. The basic slag not only doubled the concentration of phosphate in the herbage but also had an equally striking effect on the lime-concentration. Where 1 ton of limestone was applied with the slag, the concentration of nitrogen and lime was much higher than when slag alone was applied.

A most profound increase in the yield of nitrogen, lime, and phosphate was effected where no manures other than basic slag were applied. Limestone in conjunction with slag still further enhanced the yield of these three constituents to a marked extent.

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PASTURE STUDIES IV.[1] NUTRITIVE VALUE OF PASTURE HERBAGE: QUALITY OF PROTEIN

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WITH PLATE II

Introduction.—Pasture herbage has very naturally been considered the ideal food for herbivora. It is usually the cheapest 'feed' per unit of food value which can be raised on the farm. From mere observation of grazing lands or the performance of grazing stock, one must conclude, however, that there are marked differences in the nutritive value of the mixed herbage from different pastures. Furthermore, many previously excellent pastures appear to be deteriorating. In those sections where pasture is the basis of the live-stock industry any improvement in the yield and nutritive value of pasture herbage will be of considerable importance. Before improvement can be undertaken, however, the factors which are responsible for the difference between pastures must be ascertained. Soil conditions and climate, of course, play a large part, particularly in determining the yield of feed. But even on soils which appear quite similar and under the same climatic conditions, the nutritive value of the herbage may still be widely different, as measured by growth of animals or by their production.

Studies bearing on the nutritive value of pasture herbage have been confined for the most part to considerations of energy value, mineral composition, or protein-content, and it may be well to examine the published results to see how satisfactorily these factors appear to account for the observed differences in feeding-values of herbage from different pastures. Before doing so, however, it may be advisable to define the term 'nutritive value', owing to the looseness with which the term has been used. Nutritive value in the strict sense must imply the feeding-value of a specified quantity of material. Hence pasture studies in which no record of the actual feeding-value of specific quantities of the herbage is available, do not really measure nutritive worth. The stock-carrying capacity of a given field, with or without chemical analyses of the herbage, is not of itself a measure of feeding-value of the herbage. For example, by appropriate treatment the yield of herbage on a pasture may often be tremendously increased and, therefore, furnish feed for an increased number of stock. The nutritive value of a given quantity of that herbage may, however, be quite unchanged by the treatment. Feeding-tests, for instance, have shown reed canary-grass to be of low feeding-value. Increasing the yield of this grass per acre may increase the carrying capacity of that acre, but unless there has also been a change in the make-up of the grass, its nutritive value will still be low.

[1] Macdonald College Journal Series No. 41. Previous contributions to this series were published as technical communications of the Macdonald College, and one—No. II—also in *Scientific Agriculture*, 1933, **14**, 57.

Nor are chemical analyses of pasture herbage alone an infallible guide to nutritive value. The fact that the herbage of one pasture contains, or by treatment can be made to contain, 30 per cent. of protein as compared with another which analysed but 20 per cent. is of little significance unless it can at the same time be shown that the additional protein affects its feeding-value. Similarly with mineral analyses. The fact that differences occur in the calcium and phosphorus contents of different species, for instance, has been amply demonstrated. That such differences are significant nutritionally in any given case, however, must be shown by feeding-tests, for it frequently happens that herbage which deviates widely from the accepted theoretical optimum Ca : P ratio appears to have no reduced feeding-value on that account. Thus both clover and timothy, eaten in the vegetative stage, are highly nutritious. The former may show a Ca : P ratio of 10 : 1, as against timothy of 2 : 1 [1]. The optimum ratio as stated by most investigators lies between 2 : 1 and 1 : 2 in terms of the complete diet.

With this brief consideration of the scope of the term 'nutritive value', we may turn to the question of the factors that determine feeding-value, with particular reference to pasturage.

Energy value.—In general, energy value will be closely correlated with the dry-matter and the fibre contents of the herbage, and will, of course, be directly related to the feeding-value. All three of the primary nutrients contribute to the energy value of a feed: the carbohydrates and proteins about equally, and the fats a little more than double either of the other two, per unit of nutrient. By weight, these three nutrients include all but the minerals and account for between 85 and 95 per cent. of the dry matter of the feed.

Sheehy [2] has shown that grasses, clovers, and weeds differ significantly in dry-matter content. From an average of a number of pastures he reports: grasses, 26–32, clovers, 20–5, and weeds, 15–20 per cent. of dry matter.

It is evident then that in mixed pasture herbage the grass-clover-weed ratio may be a factor in its nutritive value. However, one cannot say that grasses because of their greater dry matter will yield more *net energy* to the animals than the clovers, for the latter value will be influenced by the fibre of the feeds.

Fibre, although a carbohydrate, is so poorly digested that it is, in a sense, a diluent to the other nutrients of a feed. Furthermore, it often depresses the apparent digestibility of the feed because of its tendency to enclose, and hence to protect from digestive fluids, appreciable amounts of certain nutrients, especially protein.

That grasses and clovers are significantly different in fibre is indicated by studies reported by Stapledon [3], white clover containing 18·22 per cent. of fibre, Italian rye-grass 25·00, perennial rye-grass 27·00, cocksfoot 24·45, and meadow-foxtail 25·44 per cent. Thus the lower fibre in clover and the higher fibre in grasses may tend to balance the lower dry-matter content of clovers and higher dry matter in grasses. In fact, on a dry-matter basis, data from Morrison [4] indicate that, taken in bloom, or on an average of all analyses, fresh green red clover has an appreciably

higher total digestible-nutrient content than fresh green timothy. When fed as dried roughage, the clover is still slightly higher in total food-value.

In this connexion Stapledon considered that at the same stage of maturity (rapid growth) all grasses have about the same feeding-value as measured by grazing sheep, but that clovers have a higher value than grasses. Kirsch [5], however, reports appreciable differences in nutritive value of certain grasses in terms of starch equivalents, measured in digestion-trials with cows. His findings are summarized in Table 1. The equivalent T.D.N. values in this Table were calculated by the writer from the relationships given by Kriss [6].

TABLE 1. *Starch Equivalent of Grasses* (*Spikes just emerging from Leaf Sheaths*).

	Starch equivalent %	*Total digestible nutrients* %
1st group		
Meadow-fescue	45–51	51–8
Timothy	45–8	51–5
Cocksfoot	38–45	44–51
Late meadow-grass	45	51
2nd group		
Smooth-stalked meadow-grass, Brome-grass, Sheeps' fescue, Tall oat-grass, Meadow-foxtail	38–44	44–51
3rd group		
Fiorin, Reed canary-grass, Beckmannia	36–9	41–4

Compared with these values (which are on a dry-matter basis), Graves's data [7] indicate that clipped pasture herbage, on a dry-matter basis, has a total digestible-nutrient value of 71 per cent. No botanical analysis of the herbage mixture is given, but clippings were taken on grass about 25–30 days old. The fibre-content of this mixed herbage was about 23 per cent., which agrees with Stapledon's figures (p. 338) for young grasses.

A trial carried out at Macdonald College [8], using growing rabbits, substantiates the finding of Kirsch, that there is a difference in the nutritive value of certain grasses. In this trial, dried, ground reed canary-grass was fed in comparison with timothy, each being cut at about the same stage of growth as were the grasses fed by Kirsch. The trial lasted 60 days, and involved five rabbits per lot. Rabbits were individually housed and self-fed. No feed other than the grass was given. Feed-intakes were approximately equal, rabbits on reed canary-grass consuming on the average 0·2 grams more feed each per day than those receiving

timothy. Chemical analyses of the two feeds were as follows (moisture-free basis):

	Protein	*Fibre*	*N-free ext.*	*Ca*	*P*
	%	%	%	%	%
Timothy . . .	12·9	27·7	53·1	0·43	0·38
Reed canary-grass .	14·8	30·4	49·5	0·45	0·42

The results are shown in Fig. 1.

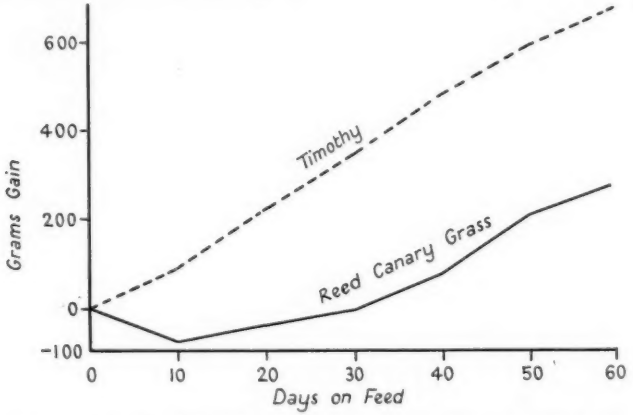

FIG. 1. Growth of Rabbits on Timothy versus Reed Canary-Grass. (Macdonald College, Expt. No. 43.)

From the limited data available, it appears that there are likely to be differences in feeding-value between the different species which make up mixed pasture herbage. Fertilization or other treatment may cause sufficient change either in flora, or possibly within a single species, to alter appreciably the nutritive value of the herbage. The data, however, are not sufficiently convincing that these differences can be fully accounted for on the basis of energy value.

Minerals.—The mineral problem in pasture herbage, in eastern Canada, centres almost entirely around the two elements calcium and phosphorus. Under certain conditions iodine, chlorine, sodium, and iron may be deficient in pasture herbage, but it has not been with the idea of enriching the feed in these elements that most pasture amendments have been designed. That individual species differ widely in their Ca and P contents has been amply demonstrated. That these elements can be altered by treatment is also admitted. It does not follow, however, that such differences necessarily affect the nutritive value of the herbage. Researches indicate that the animal requirement for Ca and P is one not only of quantity but also of balance.

As to the quantity of minerals needed daily our knowledge is far from complete. Huffman and others [9] report a daily requirement of 10–12 grams of P per day for heifers to first lactation. This is about 0·1 per cent. of the dry matter of an average ration. Archibald and Bennett [10]

state that 0·15 per cent. P in the pasture herbage is the lower limit of safety.

Lindsay [11] reports a daily calcium-intake for heifers of between 2·5 and 4·5 grams Ca per 100 lb. live weight as having been satisfactory during a trial lasting three years. In terms of the ration this represented an intake of 0·44–0·85 per cent. calcium. Data from Steenbock's laboratory [12] indicate that for rats the $CaCO_3$ requirement is between 0·5 and 1 per cent. of the total ration. This is equivalent to 0·22–0·44 per cent. in terms of Ca.

Hart [13] reports a requirement for each pound of milk of 5 grams Ca and 3 grams P.

Henderson and Weakley [14] state that rations having less than 0·35 per cent. Ca and 0·2 per cent. P give rise to a bone condition low in ash and consequently low in Ca and P.

Data reported by Archibald and Bennett [10] are interesting in showing the Ca and P of typical natural pastures.

It should be remembered that the figures given for Ca and P requirements imply a daily intake all the year round. Minerals, however, may be stored in the body, and hence liberal mineral-intake obtained on pasture may often be an insurance against poor winter rations. The apparent optimum amounts in the feed above a bare minimum sufficient to avoid recognizable symptoms of mineral deficiency are therefore indefinite.

TABLE 2. *Chemical Composition of Representative Natural Pasture (average figures for the season).* (Archibald and Bennett [10])

	Ca	*P*
	%	%
Massachusetts	0·57	0·19
Vermont	0·85	0·27
England (cultivated)	0·71	0·32
Scotland (natural)	0·46	0·29
Scotland (hill)	0·40	0·26

As to the ratio of Ca to P, investigators are agreed that for the complete diet a ratio of 2 : 1 of Ca to P is optimum, and that as the ratio deviates from this proportion the necessity for vitamin D or its substitute increases (as indicated by the incidence of rickets in growing animals). Sunlight during the pasture season in Quebec will probably greatly lessen, if not entirely replace, the need for vitamin D in the diet.

The Ca : P ratios reported for pasture herbage show wide deviations from the ideal 2 : 1 ratio. Clovers in particular tend to increase the proportion of Ca to P. Brown [15], referring to mineral versus nitrogenous fertilization, says '. . . nitrogen decreased the clover and thereby reduced the Ca : P ratio to about the theoretical ideal of 2 : 1'.

Results at Macdonald College [1] indicate that the Ca : P ratio in untreated herbage may run from 2 : 1 to 10 : 1, according to the species of plant. One series of analyses showed that, excepting timothy, annual spear-grass, and poverty-grass in June, and poverty-grass in July, all the

species found contained well over 0·15 per cent. P (averaging 0·221 per cent.). As for calcium, one sample of annual spear-grass carried 0·29 per cent. Ca, whilst all others contained well over 0·3 per cent., and averaged 0·769 per cent. Fertilization with phosphates in this study increased the Ca and the P but did not appreciably alter the ratio.

McCreary [16] reports that the P varies directly with the protein of pasture herbage. His data indicate no serious shortage of P with protein above 12 per cent. The average per cent. of P in herbage of different protein levels was:

% Protein	*% P*
12–13	0·65
13–14	0·66
14–15	0·73
15–16	0·80
16–19	0·78

Orr [17] reports correlations between CaO, P_2O_5, and N in English pastures as follows:

	Cultivated pasture	*Natural hill-pasture (portion eaten)*
CaO and N	0·29±0·13	0·33±0·15
P_2O_5 and N	0·85±0·04	0·51±0·12
CaO and P_2O_5	0·29±0·13	0·19±0·16

The high correlation between phosphorus and protein is quite evident.

It would seem that treatments which increase the quantities of these minerals may not necessarily be justified on the basis of increased nutritive value of the herbage. For instance, clovers are considered more nutritious than grasses, partly 'because of their higher calcium-content'. Actually the clovers have a very wide Ca : P ratio and an increase of clovers in the mixed herbage distorts the ideal ratio materially.

Unless there is an actual shortage of Ca or P in the herbage—and this may often be the case with P—the data do not support the implication that the higher the Ca and P the greater the feeding-value. Orr (loc. cit., p. 11) states that good pastures carry 0·7 per cent. Ca and 0·3 per cent. P. More than this would appear to dilute rather than increase the nutritive value of the herbage when it represents the entire diet. Normal growth, reproduction, and lactation are recorded on much lower levels of Ca and P intake.

Protein.—The importance of protein in the diets of all animals has been so much stressed that an exaggerated idea of the amounts or proportions of this nutrient required by animals for ideal nutrition is all too common. Whether protein is burned as a source of energy or used for tissue-growth and repair depends upon (*a*) the amount present in the diet, and (*b*) its nature or quality as measured by its amino-acid make-up.

In general, diets in which the quality of protein is satisfactory should carry between 9 and 16 per cent. of protein, depending upon the age of the animal and the production expected. Proteins incomplete in the

essential amino acids will have a low biological value. This may be partly compensated for by larger intakes, and may explain the tendency to consider desirable those pasture treatments which increase the protein-content of the herbage.

The proportions of digestible crude protein called for in Morrison's Feeding-Standards (1923) for different classes of grazing stock (exclusive of calves under 500 lb.) range from 4 to 11 per cent. of the dry matter of the ration, depending upon the class and age of the animals in question. Taking the average digestibility of protein as 75 per cent., these requirements in terms of total crude protein become 5 to 15 per cent.

Since this standard represents results of many years of experimental feeding, it may be taken as a reliable guide when the protein is supplied from sources commonly found in the ordinary mixed ration. Mitchell [18] intimates that the biological value of such protein mixtures probably does not exceed 50 per cent. Unless, therefore, the quality of protein in pasture herbage is poorer than that of average mixed dairy rations, the percentage protein required in such herbage for satisfactory nutrition would not exceed the figures in the previous table (assuming, of course, that pasturage is the sole food). It may also be mentioned that the biological value of a protein decreases materially as the level of protein-feeding is increased. Beef-liver proteins at 8 per cent. level have shown a biological value of 77, but at 16 per cent. level this dropped to 58 [19].

Comparison of the protein-content of several natural pastures, reported by Archibald and Bennett [10], with the feeding-standard requirements, suggests quite clearly that quantity of protein is probably not a limiting factor in the nutritive value of the young herbage (see Table 2, p. 341). Further, it is perhaps significant that some common pasture weeds, stated by Sheehy [2] to have low feeding-values, nevertheless have high protein-contents [3].

TABLE 3. *The Chemical Composition of a number of Miscellaneous Herbs of Grassland in comparison with White Clover, Italian Rye-grass, and* Nardus. *Percentage based on Dry Matter.* (Stapledon [3])

Species	*Crude protein* %
Wild white clover	26·20
Italian rye-grass	12·09
Daisy	16·73
Dandelion	19·36
Yarrow	19·90
Knapweed	20·20
Buttercup	16·20

A feeding trial reported by Graves [7] does not indicate that the high protein of pasture herbage (13·1–20·50 per cent. of dry matter) when fed to dairy cows increased its nutritive value over a ration of grass hay in which the protein level was much lower (9·9–14·9 per cent.).

Watson, Procter, and Ferguson [20] state as one of the effects of nitrogen-treatment of pasture 'an increase in the protein-content of the

herbage, more particularly at the most critical periods when the percentage in the non-nitrogen-treated grass falls to a very low level'. (This low level occurred in August when the herbage analysed between 13 and 14 per cent. protein.) Data taken from this same report, however, fail to substantiate the implication that the increased protein caused an increase in live-weight gains, as shown in Table 4.

Other data from the same source [20] indicate substantially the same result, viz. that the higher percentage of protein in nitrogen-treated pasture herbage is not necessarily reflected in an increase in live-weight gain of sheep.

TABLE 4. *Rates of Gain of Sheep, and Percentage Protein in the Feed (Pasture Herbage).* (Arranged from data in *J. Agric. Sci.*, 1932, **22**, 257)

Stock grazed	*Dates*	*Nitrogen-treated pasture*		*Natural pasture*	
		Av. daily gain	*Protein in grass*	*Av. daily gain*	*Protein in grass*
		lb.	%	lb.	%
Shearlings	April 29	0·40	22	..	22
	May 13	0·60	21	0·75	16
	May 28	0·25	21	0·30	15
	June 11	0·20	22	0·20	15
	July 25	0·08	20	0·20	20
Lambs	Aug. 12–Sept. 24	0·13	19	slight loss	19
	Oct. 14–Nov. 4	0·03	18	,, ,,	14

TABLE 5. *Gains of Sheep on Nitrogen-treated versus Natural Pasture.* (*J. Agric. Sci.*, 1932, **22**, 257)

Stock fed	*Days fed*	*Nitrogen-treated pasture*		*Natural pasture*	
		Av. daily feed	*Daily gain*	*Av. daily feed*	*Daily gain*
		lb.	lb.	lb.	lb.
Shearlings	69	3·7	0·36	3·6	0·35
Lambs	44	1·9	0·13	1·7	loss
,,	21	1·9	0·03	1·9	,,
		Total protein		*Digestible protein*	*Total digestible nutrients*
Percentage composition of the herbage (average of season):					
Nitrogen-treated		18·5		14·5	71·0
Natural pasture		15·0		10·8	70·3

It is perhaps worth noting that in Watson's trials the younger animals failed to gain on the natural pasture, whilst the shearlings made satisfactory progress. Close folding is offered by the investigators as the

probable cause. In the light of results at Macdonald College, it might be suggested that quality of protein may have been at least partly responsible, young animals, of course, being more likely to react unfavourably to poor quality of protein than more mature ones.

Nutritional Studies on Mixed Pasture Herbage at Macdonald College[1]

In view of the known differences in the nutritive values of herbage of different pastures and the failure of the suggestions usually advanced to account satisfactorily for such differences, together with a theory, thus far practically unexplored, that possibly quality of protein might prove to be a factor of significance in this regard, a feeding experiment was outlined in 1933 at Macdonald College in which it was planned to feed, to newly weaned rabbits, clipped dried herbage obtained from natural and from fertilized pastures. In addition to the lot in each series which was to receive only the grass, other lots were to receive in addition to the basal diet of grass a supplement consisting of one of the essential amino acids, or a mixture of two or more of them.

To date, the first feeding trial (Trial No. 44) of this experiment has been completed. Six lots of five rabbits each were fed for a period of 28 days. Each rabbit was housed in a separate cage, permitting individual records of feed-intake and gains in live-weight (see Plate 11).

The protein, fibre, Ca and P contents, and the approximate botanical composition of the basal diets were as follows:

TABLE 6. *Approximate Botanical Composition and Protein-content of Pasture Herbage fed in Trial No. 44*

Species	*Unfertilized herbage*	*Fertilized herbage*
	%	%
Clover	4	15
Red fescue	5	6
Red top	27	21
Timothy	8	10
Poverty-grass	12	12
Paint brush	10	11
Other weeds and grasses too scarce to list	34	25
	100	100
Dry-matter basis		
	%	%
Protein	14·70	16·70
Dry matter	94·68	94·85
Fibre	24·34	22·77
Ca	0·92	1·04
P	0·28	0·37

The area from which the fertilized herbage was clipped received, about a month before the first clipping was made, an application of

[1] These studies constitute a part of the general pasture project undertaken at Macdonald College, and are made possible by financial assistance from the Quebec Department of Agriculture.

muriate of potash and superphosphate at the rate of 225 and 700 lb., respectively, per acre. Three clippings were made during the season and compounded for feeding. The detail of the diets fed in each lot is given in Table 7.

The daily feed-allowance for each rabbit was the same in all lots. For the first seven days, 100 grams of air-dry feed were fed per rabbit per day. This allowance was increased for the next 14 days to 125 grams. For the last seven days it was necessary, because of an error in shipment of cystine, to reduce the daily allowance of the ration to 115 grams. The effect of this reduction is noticeable in the growth curves. The daily allowances were based on the consumption of similar rations in previous trials and represented about 85 per cent. of the average daily consumption under self-feeding. Apart from a small unavoidable wastage, which was approximately the same for all individuals and amounted to about 1 per cent. of the allowance, all feed offered was consumed. Water was supplied *ad lib.* in cups attached to each cage-wall. The results are shown in Fig. 2.

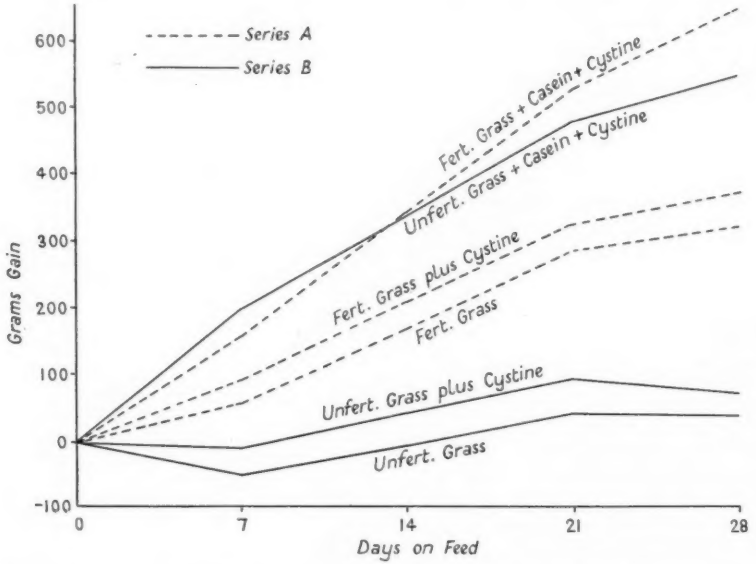

FIG. 2. Growth of Rabbits on Fertilized versus Unfertilized Mixed Pasture Grass. (Macdonald College, Expt. No. 44.)

It is evident from this study that whilst cystine was not a limiting factor for growth in these diets, the addition of a mixture of the essential amino acids, represented by casein, not only increased growth but made equally efficient the fertilized and unfertilized herbage.

That quality of protein may be a factor in the nutritive value of pasture grass would thus appear to be established. Further work, it is

hoped, will yield more definite information as to what amino acids may be deficient in the unfertilized grass, and whether fertilization of pasture may actually alter the quality of protein in the herbage.

TABLE 7. *Percentage Composition of Feed-mixtures used (Trial No. 44)*

Ingredients	*Series A*			*Series B*		
	Lot I	*Lot III*	*Lot V*	*Lot II*	*Lot IV*	*Lot VI*
	%	%	%	%	%	%
Fertilized grass	92·6	90·0	55·5	..	..	..
Unfertilized grass	..	..	..	99·0	96·0	59·5
Oat hulls (1/2) } Sucrose (1/2) }	6·4	8·6	38·37	..	2·6	34·37
Salt	1·0	1·0	1·0	1·0	1·0	1·0
Casein	..	..	5·0	..	..	5·0
Cystine	..	0·4	0·13	..	0·4	0·13
Dry-matter basis						
Percentage crude protein	15·66	15·72	14·75	14·56	14·60	14·12
Percentage Ca	0·97	0·99	0·64	0·91	0·91	0·61
Percentage P	0·35	0·34	0·28	0·27	0·27	0·24

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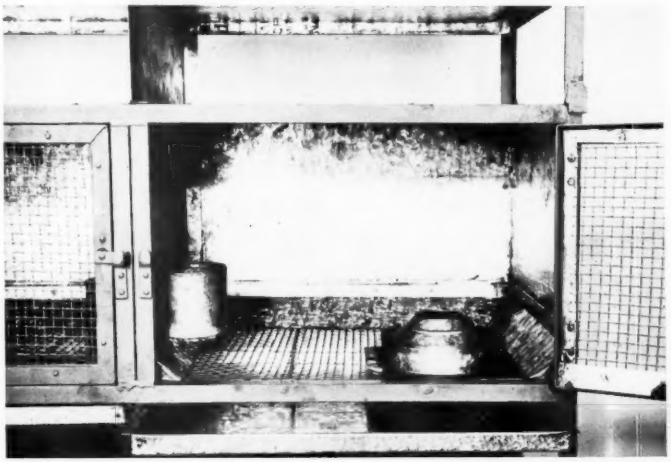
A six-cage section of feeding-pens used in this study for rabbit feeding



A single feeding-cage

THE INFLUENCE OF MATURITY AND RAINFALL ON THE PROPERTIES OF LATERITIC SOILS IN MAURITIUS

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MAURITIUS is an island situated in the South Indian Ocean, latitude 20° to 20° 30′ south, longitude 57° 18′ to 57° 48′ east of Greenwich, and has a total area of 720 square miles. The island is extensively cultivated, upwards of 47 per cent. of the whole area being under cultivation, the primary crop being sugar, of which the annual production is about 230,000 metric tons. Its geological history is simple, for the island originated probably as a volcanic upthrust, with basaltic intrusions. Although there are many sharp mountain ranges and isolated peaks, the general form of the island is conical, the highest point of the central plateau being approximately 1,900 ft. above sea-level. The climate is influenced to a great extent by the prevailing SE. trade winds, which bring a plentiful supply of rain to the windward slopes [1]. On the leeward side, the higher slopes receive a fairly copious rainfall, but the lower slopes are distinctly deficient. In general the isohyets follow the contours, but in all cases they descend to lower levels on the windward side than on the leeward. The variation in rainfall is great, and in the space of a few miles one can pass from a belt receiving on the average only 25 to 50 in. of rain per annum to one receiving 150 in. or more. During the passage of cyclonic disturbances near the island, precipitation may be extremely heavy and general, and during these torrential downpours a certain amount of soil is lost by washing. In general, however, the slopes of the cultivated soils are gentle, so that erosion is not as a rule a very serious factor. The districts of low rainfall have a somewhat higher temperature than those with a high precipitation; these temperature-differences are, however, so small in comparison with those in rainfall that their effect as a soil-forming factor has in all probability been masked. The climate may be regarded as a tropical oceanic climate, of a type somewhat similar to that of Hawaii. At the Royal Alfred Observatory, altitude 180 ft. above sea-level, the mean annual temperature is 23° C. and the maximum and minimum monthly temperatures are 26° C. and 19·9° C., respectively.

In general, the soil-producing rocks consist of doleritic basalt, in which the minerals plagioclase, olivine, augite, and magnetite predominate [2, 3]. Some very fine-grained basalts exist, as does phonolitic trachyte. The parent-rock material of the great majority of the soils of the sugar-cane areas is undoubtedly the doleritic basalts, so that the influence of the rainfall is not masked by important differences in the parent material. In these rocks the molecular silica-alumina ratio is approximately 5·8 to 1, and the ratio of Fe_2O_3 to $Al_2O_3+TiO_2$ is 0·77 to 1.

The soils under discussion may be divided into two chief groups: (*a*) the typical mature soils, i.e. those in which the decomposition of parent rock has proceeded to such an extent that there are now no

undecomposed minerals in the soil complex. Although large round-shaped stones or boulders of compact structure may be found in such soils, they are free from small stones and gravel; (*b*) the typical immature soils, the properties of which are affected by the presence of minerals still in the process of weathering. They are characterized in the field by the presence of a more or less high proportion of small, angular stones of vesicular structure and gravel, which are a source of potential fertility for the future. The large stones in mature soils are generally encrusted with a layer of about 0·5–1 in. thick where the process of laterization is still proceeding, but inside this surface-layer the rock is perfectly fresh and unaltered, judging from its appearance to the naked eye. It would seem that the immature soils are formed from the comparatively more recent lava flows, as instances have been observed where the mature soils, known locally as *terres franches*, are overlain by a sheet of basaltic lava which has subsequently given rise to an immature soil, known in the island as *terres rocheuses*. One such instance is at Rivière la Chaux, Beau Vallon S.E., where on one side of the river a fossil mature soil is overlaid by a younger sheet of basalt which has given rise to a rocky soil, whilst on the other side of the river the mature soil is being cultivated. The interval of time between these successive flows must in some instances have been very great, as the depth of the underlying soil is considerable. The mature soils will naturally show the action of rainfall as a soil-forming agency to a fuller degree than the younger soils, as their properties are more in equilibrium with the external conditions producing them. It will be shown that in many ways the properties of the immature soils vary in a similar way to those of the first class, although the absolute values are different.

In the present paper the properties of the top soils only have been considered, and therefore it is possible that certain of them have been changed as the result of cultural practices, notably the organic-matter content and the properties related to it. However, the organic matter is decomposed very much more rapidly, and consequently reaches a state of equilibrium very much more quickly than the soil-forming minerals.

In all, fifty-four mature soils and nineteen immature soils have been examined, and each of these groups has been subdivided into five divisions, according to their mean annual rainfall. In some of these divisions the number of representatives is rather small, but in spite of this they fall into their places in the series. This is particularly the case in the immature soils, where three divisions are represented by a maximum of three samples. The mean figures for each of these several groups are given in the tables that follow (see Appendix), where the figures for the mature and immature soils produced under similar rainfall conditions are placed side by side, whilst the different rainfall groups are placed in columns. Thus the effect of rainfall is seen in the columns, whilst the influence of age is illustrated by the pairs of figures in the rows.

Colour.—The first property which obviously varies with the climate is that of colour. In the mature soils, as shown in Table 1, the colour-

changes taking place on passing from an area of low rainfall to one of high precipitation are from red, or red with a purplish tinge, through brownish-red and yellowish-brown to brownish-yellow. These changes are very marked in the field, and for comparing the colours of the air-dried samples the colour chart in *Terres rouges et Terres noires basaltiques d'Indochine*, by Yves Henry, was employed. It seems highly probable that these colour-changes are intimately linked with the state of hydration of the soil constituents, particularly iron oxide, as the combined water, i.e. water of hydration, shows a very definite and regular increase with increased precipitation; the range being from 12·1 to 19·5 per cent. The colours of the immature soils are generally somewhat darker than those in the corresponding groups of mature soils, but in the drier regions they are totally different, one type being red and the other brown; when wet the latter group is almost black, but when air-dry is brown with a greyish tinge. Their colour is not accurately represented in the colour chart mentioned above, but they are intermediate between *Havane foncé* and *Brun*. It will be seen that in group D the colours for both types of soil are the same, and it must be pointed out that the two representatives of the immature soils in this grouping do not seem to be typical, but are probably intermediate between the typically mature and immature soils.

Mechanical composition.—Whilst any figures for stones and gravel above 2 mm. diameter can only be approximate, they are nevertheless of interest as they do give some idea of the vast difference between the two types of soil; and also it would seem that increased precipitation results in a decreased amount of stones and gravel. The figures for the inorganic colloids are very striking, and those for the mature soils show a very decided and progressive reduction in the amount of these fractions as we pass from the dry to the wet districts, the reduction being from 73 to 45 per cent. In those soils with the higher contents, there are only small proportions of the sand fractions, but in those with the lower contents, the sand fractions are greater in quantity. These constituents, however, are not normal sand; they do not consist of unweathered fragments, but of concretions, which represent a more advanced stage in the decomposition of the original material than does the clay fraction. Compared with the corresponding clays, these concretions contain approximately the same amount of silica, more alumina, and less iron oxide, and it is suggested that these bodies may represent the final stages in the process of laterization.

In the case of the immature soils, however, no such relationship between clay-content and rainfall is noted, the clay-content of the various groups remaining more or less constant. The sand-content of these soils may be comparatively high, but in this case the sand consists of partly decomposed rock material and its chemical analysis shows that its composition is intermediate between that of the original rock and that of the corresponding clay. This sand may therefore be regarded as a potential source of fertility, as during its further decomposition it will set free plant-food materials.

Organic matter.—As suggested above, the organic content of soils may be affected by cultural methods. Be that as it may, from the figures given

in Table 2, its quantity and quality would definitely seem to be related to the rainfall. Thus the organic matter in the mature soils definitely increases with the precipitation, and at the same time the carbon-nitrogen ratio becomes wider. It must be borne in mind that only the top soils are under consideration and it is for this reason that the average contents are so high. The fact that the soils of the wetter areas contain more organic matter with a wider C/N ratio than those of the dry areas is probably accounted for by the different intensities of the various microbiological processes in the various localities. The rate with which these actions take place depends upon several factors of which the chief are: temperature, moisture, air-supply, supply of bases and soil acidity. The temperature in the wet districts is lower than in the dry, so that this will depress the rate of destruction of organic matter in the former regions. However, the combined influence of the other factors is in all probability much greater than that of temperature alone, and it will be seen that all these other factors may be governed by precipitation. Many of the upland soils suffer from an excess of moisture, and consequently the air-supply of the organisms is probably diminished. Soil acidity and poverty of bases are common in these soils, and it will be shown later that these properties are intimately connected with rainfall. Consequently it is but reasonable to suppose that either directly or indirectly rainfall is principally responsible for these differences in the quantity and quality of the organic matter. In the dry districts, where the temperature is higher and where the soils are more nearly neutral and well provided with exchangeable bases, the destruction of organic matter is intense, with the result that this component has a close C/N ratio and is small in quantity. Where the conditions are the reverse we find more organic matter with a wider C/N ratio.

The same points may be noticed as regards the organic contents of the rocky hills, with this great difference—that these soils contain much more organic material than the soil in the corresponding groups of the free soils. Why this should be so is obscure; the reason may be that the soils are more retentive of water thus resulting in a smaller air-supply, or it may be that these soils which are not yet fully mature contain some other factor which has a depressing effect upon its micro-flora.

Influence of rainfall and maturity on leaching of silica.—The rocks from which the majority of cultivated soils in Mauritius have been formed consist of doleritic basalts of fairly constant composition that are practically free from quartz. Hence any silica found in the soils must be derived from this original combined silica. Consequently the amount of residue, insoluble in concentrated hydrochloric acid, which chiefly consists of silica, may be taken as a rough guide of the intensity with which it has been removed during the processes of soil formation. The figures given in Table 3 show that the silica has been leached to a much greater extent in those soils formed under conditions of high rainfall than in those in dry districts, and at the same time there has been an increase in the proportions of alumina (including titanium dioxide) and ferric oxide; this being particularly evident in the mature soils. A better method for following the course of the decomposition is, however, given

by the molecular ratios of the principal rock and soil-forming components, such as silica, alumina, and ferric oxide. In the original doleritic basalt the silica-alumina ratio is approximately 5·8, whereas this ratio for the mature soils varies from 1·87 in group A to 0·43 in group E and from 2·34 to 1·32 in the corresponding groups of the immature soils, thus showing that in all soils the silica molecules must have been removed at a much quicker rate than those of alumina. These figures also show that the silica has been the more completely removed in the soils formed under conditions of high precipitation, and that the removal has been less complete in the immature soils. Furthermore, in the original rock material the ratio of ferric oxide to alumina is approximately 0·77, and in practically all the soils between 0·6 and 0·7, so that these two substances may be considered equally permanent fractions. The increased combined-water contents of the more highly leached, and therefore more highly laterized, soils is probably accounted for by the increased content of the lateritic elements, and the higher degree of hydration of these constituents.

Clay analysis.—The more usual method of estimating the degree of laterization is by considering the results of the bulk analyses of the clay-fractions [4]. The clay from three soils of each group of mature soils, 25–50 in., 50–100 in., and 100–150 in. of rainfall, and five from immature soils were analysed by fusion methods and the results are given in Table 5. It will be noticed that the molecular ratios and the combined water for the clay fraction and for the whole soil vary in similar ways, the ratios for the clay fraction being, however, a little lower. These results emphasize the important part which leaching plays in silica removal, and the extreme degree to which it has acted in some of our soils. Thus, supposing that all the original alumina has remained in the soil, none being lost in the drainage water, then in the clay fractions for soils situated within the range 100–150 in. more than 90 per cent. of the silica has been removed by leaching, whilst at the other end of the scale about 70 per cent. has been lost. The number of clays analysed from the immature soils is too few to give really reliable comparisons, yet they seem to indicate that the clays from these soils have undergone the process of laterization to a slightly less degree than have the mature clays, i.e. the analytical results are similar to those of the whole soil.

Base-exchange relationships.—Concurrently with the removal of silica during the process of laterization, bases, such as calcium, magnesium, potassium, and sodium, are also lost in the drainage water. This observation is very well illustrated by the figures given in Table 4, which show that the sums of exchangeable bases in the mature and immature soils in the 25–50 in. range are 24 and 32·7 mg.eq. respectively, but that they fall progressively to minimum values in the 125–150 in. range of 4 and 8 mg.eq. respectively. The figures point out the extreme poverty of the most highly leached soils as regards exchangeable bases, the largest fraction of which is calcium. Again, if we consider the proportion of calcium in the sum of the exchangeable bases, we find that the proportion rises from 67 to 92 per cent. in the mature soils as we pass from the dry

districts to the wet, thus accentuating the poverty of the latter as regards other exchangeable bases. The increase of exchangeable calcium expressed as a percentage of the sum of exchangeable bases is also seen in the immature soils, but not quite to the same degree. Not only does the sum of exchangeable bases drop in the wet districts, but also the total exchange-capacity at pH 7 in both series, but it must be noted that this capacity, as well as the content of exchangeable bases, in the immature soils is higher than that in the mature soils. The sum of the exchangeable bases expressed as a percentage of the total exchange-capacity (at pH 7), i.e. the percentage base-saturation, is nearly the same for the two different classes of soils in similar rain-belts, and in each class the percentage saturation falls consistently as precipitation increases. The pH values show a very close correlation with this property, so much so that independently of any consideration regarding the age of the soil, the one can be calculated from the other with a fair degree of accuracy.

It is generally considered that the base-exchange capacity of soils is intimately connected with the clay and part of the organic matter in the soil, and also that these colloidal fractions are chiefly responsible for the retention of hygroscopic moisture, i.e. that the factors are practically the same. When coefficients of correlation between the total base-exchange capacity and hygroscopic moisture are calculated separately for the different soil groups (mature and immature), correlations of a medium order are discovered. These correlations, however, are not reflected in the arithmetic means for the hygroscopic moisture at 50 per cent. relative humidity, probably because the correlation is not sufficiently marked to be shown by the average figures. The figures given in Table 4 show, however, that although the differences in hygroscopic moisture within the two groups are not very well marked, yet they show important differences between the groups. The same point may be noticed with regard to the total exchange-capacity, i.e. that the differences between groups is greater than within them. Consequently, when all the soils are considered together, the coefficient of correlation between these two factors becomes high (+0·80).

Discussion.—A consideration of the points discussed must lead to the conclusion that practically all the properties of Mauritius soils, whether mature or immature, show a very intimate relationship with the average rainfall of the area in which they are situated. The rainfall is not equally distributed throughout the year, the heaviest precipitation occurring during the hot summer months from January to April and the lightest in the months September to December. The natural drainage conditions of the soils under discussion are good and there is very little likelihood of any large amount of water finding its way to the surface from the sub-soil during any dry period, and consequently it is highly improbable that the surface soil is enriched by the bringing up to the surface of soluble salts from the deeper layers. When this free drainage is absent, or where the soil may be enriched by means of soluble salts in solution, different soils may be produced, but these soils are definitely small in area, and are not as a rule brought under cultivation.

In consequence, a very good estimate of the natural properties of a

soil can be made if it is known whether the soil is mature or not, and what is the rainfall. Naturally, the more ephemeral of the soil properties may be considerably modified by changes in the cultural system, as for instance the lime status. We know that the natural state of the most highly leached soils is an acid one, practically devoid of exchangeable calcium. This status may easily be changed by large and regular applications of liming materials, but it is certain that if these applications be discontinued, the soil will gradually revert to its former acid condition.

It is but reasonable to think that the best basis on which to classify soils is the character of the soils themselves. When, however, it can be shown that practically all the soil properties show a close relationship to one factor responsible for their formation, there is no objection to the use of this factor as an aid in classifying them. It has been shown that the two factors which are by far the most important in influencing the formation of soils in Mauritius are those of age and leaching. The age can be determined by the morphology of the soil, whilst the mean annual rainfall is a measure of the leaching effect. On these grounds, therefore, we consider that under the special local conditions a knowledge of the climatic conditions, especially rainfall, is a very valuable aid in soil classification.

The figures herein reported offer valuable evidence of the genetical relationship between the red soils and the highly laterized brownish-yellow soils. It has been shown that increasing rainfall results in a gradual transition of soil properties from those of red soils to those of brownish-yellow soils. It would thus appear that the red soils are formed by means of lateritic decomposition, but without a high leaching-factor, whereas the brownish-yellow highly laterized soils are derived from lateritic weathering accompanied by a high leaching-factor [5]. A further interesting point is that within the space of a few miles, representatives of two great groups of soil—the red soils and the laterites—may be encountered, both having been derived from similar parent-rock material. Between these extremes all intermediate types may be found.

It is also obvious that the age of the parent-rock formation is also extremely important. Erhart [6], from observations made in Madagascar, suggests that all the old volcanic rocks undergo lateritic alterations in a humid tropical climate up to an altitude of 2,000 metres. At the same time he states that the recent volcanic rocks do not yield lateritic soils when they are weathered. Judging from this description of these soils from the recent formations, they would appear to correspond with the soils which we have classified as immature. Yet a consideration of the figures given above indicates that the decomposition has been of a lateritic type, but that the process has not approached finality on account of the age factor. The effect of the age factor, like that of the rainfall factor, is cumulative, so that one may find types intermediate between the typical mature soils and those which are most immature, and these will have properties intermediate between the two extremes.

The descriptions given by Borden [7] and Richter [8] of the Hawaiian soils show very great similarity with this description of the mature soils of Mauritius, but it must be pointed out that the immature soil type

herein described does not seem to exist in Hawaii. The parent-rock material of both is basalt, and the climates are similar, resulting in similar decomposition products.

Complete soil-profile studies have not been conducted with all these soil types, in fact the carrying out of such an examination with some soils would be extremely difficult, as the mature soils are of very great depth. In certain of these, pits more than 30 ft. deep have been dug without reaching the parent-rock material, and except at a depth of about 9 in., when the surface soil stops, there has been no sign of a sudden alteration. The profile of an immature soil is, however, comparatively shallow.

In this study only the properties of the surface soils have been considered. The few profiles examined in Mauritius have shown no definite horizon, except the surface one, which may be darker coloured on account of its organic content. This is quite in keeping with our knowledge of lateritic soils, to which class Mauritius soils belong. The minor differences of the cultivated soils can best be detected by analysing the surface soil, which is the layer of particular interest to the planter; to him a knowledge of these variations is of great value, as it enables him to manage the soils of the various climatic zones in the most economical manner.

The average figures in the various tables have been calculated from the results given in Bulletin No. 4 of the Sugar-cane Research Station, Department of Agriculture, Mauritius.

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APPENDIX

TABLES SHOWING THE GENETIC RELATIONSHIP OF TOP SOIL

Mean analytical figures for cultivated soils grouped according to intensity of annual precipitation and maturity stages.

TABLE 1. *Colour of the Air-dried Samples*

(According to colour chart in Yves Henry's book *Terres rouges et Terres noires basaltiques d'Indochine*)

No. of top soils examined			*Mean annual rainfall*	*Per cent. of soils in each group showing the following colours*			
Mature		*Immature*		*Mature*		*Immature*	
	Terre franche (typical)	*Terre rocheuse (typical)*	*Range in inches*		%		%
A	10	5	25–50	Brun rouge	34	Havane foncé brunâtre	80
				Rouge brun	66	Havane foncé	20
B	24	6	50–75	Brun rouge & rouge brun	15	Havane foncé brunâtre	50
				Havane foncé	60		
				Havane clair	25	Havane foncé	50
C	10	3	75–100	Havane foncé	20	Havane foncé brunâtre	34
				Havane clair	80	Havane foncé	66
D	7	2	100–125	Havane clair	100	Havane clair	100
E	3	3	125–150	Havane clair	100	Havane	100

TABLE 2. *Mechanical Composition and Organic Matter*

Mean annual rainfall		*Stones and gravel*		*Inorganic colloids*		*Organic matter*		*C/N ratio*	
Range in inches		*200–2 mm. diam. % whole soil*		*< 2μ % dry soil*		*Org. carbon × 1·724 % dry soil*			
		Mature	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*
A	25–50	8	56	73	49	4·0	6·1	9·1	9·7
B	50–75	4	40	67	53	4·9	5·6	10·4	9·6
C	75–100	5	43	56	49	5·3	7·7	11·1	10·8
D	100–125	5	19	49	44	5·7	9·4	11·2	11·3
E	125–150	2	33	45	43	6·1	10·2	12·7	11·8

TABLE 3. *Chemical Analysis (conc. HCl method)*

Influence of rainfall and maturity on leaching of silica (laterization)

	Annual rainfall	*Insoluble residue* (*approx.* SiO_2) % *dry soil*		Fe_2O_3 % *dry soil*		$Al_2O_3+TiO_2$ % *dry soil*		*Molecular ratio* $SiO_2/Al_2O_3+TiO_2$		*Molecular ratio* SiO_2/R_2O_3		*Combined water* $H_2O(+)$ % *dry soil*		*Ratio of* Fe_2O_3 *to* $Al_2O_3+TiO_2$	
	Range in inches	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*
A	25–50	32·8	36·0	20·2	16·6	29·9	26·5	1·87	2·34	1·32	1·48	12·1	11·5	0·68	0·63
B	50–75	27·7	32·0	21·6	17·6	31·2	29·0	1·53	1·91	1·02	1·37	13·4	12·7	0·69	0·61
C	75–100	19·8	29·8	23·3	19·5	33·2	29·3	1·10	1·74	0·76	1·20	15·6	13·7	0·70	0·66
D	100–125	12·7	17·5	24·4	23·8	38·7	32·1	0·56	0·93	0·40	0·63	18·6	17·0	0·63	0·74
E	125–150	9·9	23·1	26·9	20·4	39·4	30·4	0·43	1·32	0·29	0·82	19·5	15·1	0·68	0·67

TABLE 4. *Exchangeable Bases and Reaction*

Influence of rainfall and maturity on leaching of bases

	Annual rainfall	*Hygroscopic moisture at 50% R.H.*		*Total base exchange capacity at pH 7* *mg.eq. % dry soil*		*Exchangeable hydrogen* *mg.eq. % dry soil*		*Sum of exchangeable bases* *mg.eq. % dry soil*		*Exchangeable calcium* *mg.eq. % dry soil*		*Exchangeable calcium % sum of exchangeable bases*		*% base saturation*		pH *value* *Collodion-bag method (color.)*	
	Range in inches	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*
A	25–50	6·7	10·4	29·5	43·5	5·5	10·8	24·0	32·7	16·1	24·4	67	74	81	75	6·8	6·7
B	50–75	6·4	9·8	26·2	36·4	10·3	12·5	15·9	23·9	12·8	17·9	81	75	61	66	6·3	6·5
C	75–100	6·4	9·8	22·9	35·9	14·7	19·2	8·2	16·7	7·4	13·9	90	83	36	47	5·95	6·1
D	100–125	6·8	9·8	22·3	29·1	16·9	21·1	5·4	8·0	5·0	6·3	93	80	24	28	5·7	5·95
E	125–150	6·5	10·2	20·6	33·6	16·6	25·6	4·0	8·0	3·7	6·3	92	80	19	23	5·6	5·7

TABLE 5. *Chemical Analysis of Inorganic Colloid* ($< 2\mu$), *Fusion Method*

No. of fractions analysed		*Annual rainfall*	*Molecular ratio* SiO_2/Al_2O_3		*Molecular ratio* SiO_2/R_2O_3		*Combined water* $H_2O(+)$	
Mature	*Immature*	*Range in in.*	*Mature*	*Immature*	*Mature*	*Immature*	*Mature*	*Immature*
3	1	25–50	1·68	1·70	1·13	1·19	14·3	16·9
3	2	50–100	0·94	1·32	0·62	0·97	16·4	15·8
3	2	100–150	0·37	0·65	0·22	0·51	19·0	17·4

SOIL SURVEY OF NORTH SHROPSHIRE[1]

Pt. II. CLASSIFICATION OF SERIES AND TYPES

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Basis of Classification

IN Pt. I of this communication the soil series was described as a unit embracing all those soils that are derived from the same or similar parent materials, formed under the same conditions, and showing a general similarity in the profile. In actual practice this general definition is interpreted by:

1. A description of the geological origin and nature of the parent material, to be expanded, if necessary, to include the mode of deposition.
2. A description of the topography and elevation.
3. A description of the water-relationships, drainage, rainfall, &c.
4. A description of the vegetation, particularly if it be natural.
5. A description of the soil profile.

1. *Geological origin and parent materials.*—This factor has been dealt with in detail in Pt. I. The question of including a description of the mode of formation under a separate heading has caused some ambiguity. In line with American practice, some surveyors hold that it refers to the mode in which the parent materials have been deposited, e.g. alluvium, drift, &c. Others prefer to regard such descriptions as included by inference under the heading 'Parent Materials'. In the following descriptions of the series, the latter practice has been adopted, and it is recommended for general adoption.

2. *Topography and elevation.*—This heading includes a broad description of the nature of the country in which a series is found. Such terms as depressed, flat, sloping, steeply sloping, and undulating are used for describing series, and are represented by symbols on the maps.

3. *Water-relationships.*—Two broad divisions, i.e. free, and impeded drainage, are recognized. Further subdivision of the degrees of impedance are necessitated by the nature of the causes, and have been referred to in Pt. I.

4. *Vegetation.*—A description under this heading is useful and shows whether the series is associated with natural or cultivated plant-life. Unfortunately, few instances of natural vegetation other than 'heaths' can be distinguished with certainty in the area surveyed.

5. *Profile-description.*—This term is used in the way generally accepted by soil workers. It includes measurements and descriptions of each successive horizon as far down as the unchanged parent material, or, at any rate, to a point where the effects of weathering may be assumed to

[1] Published for the Excursion Committee of the Third International Soil Congress, 1935.

TABLE 1

		A_0 (6–9 in.)	A_1 (9–19 in.)	B_1 (19–23 in.)	B_2 (23–35 in)	C (below 35 in.)
Stones		..	..	..	..	..
Fine gravel		..	..	..	..	..
Coarse sand	per cent.	41·0	64·4	50·6	70·7	73·5
Fine sand	,,	21·9	22·0	12·5	20·6	17·5
Silt	,,	9·6	7·6	6·9	1·8	4·2
Clay	,,	2·7	1·3	8·8	2·2	3·3
$CaCO_3$	,,	..	..	..	..	..
Loss on solution	,,	1·43	0·45	2·6	1·54	0·15
Moisture	,,	3·54	0·67	3·5	1·52	0·90
Loss on ignition	,,	25·05	3·04	15·55	2·68	1·58
Exchangeable CaO	,,	0·044	0·014	0·021	0·006	0·043
C	,,	14·88	1·63	17·14	0·40	0·04
N	,,	0·51	0·12	0·30	0·07	0·03
C/N ratio		29·24	13·36	23·48	5·76	1·43
pH		3·70	3·13	3·73	4·75	4·75
Composition of the clay fraction						
SiO_2	per cent.	52·62	54·61	44·78	38·54	46·85
Fe_2O_3	,,	10·10	2·89	5·18	16·45	9·97
Al_2O_3	,,	28·51	33·05	42·54	40·00	34·63
TiO_2	,,	1·34	2·21	2·06	0·85	0·43
SiO_2/R_2O_3		2·55	2·66	1·66	1·19	1·94
SiO_2/Al_2O_3		3·13	2·30	1·79	1·51	2·29
SiO_2/Fe_2O_3		13·86	50·25	22·99	5·75	12·49

The percentage of stones and fine gravel are calculated separately and not entered as part of the mechanical analysis.

TABLE 2

		0–8 in.	8–11 in.	11–18 in.	18–34 in.	Below 34 in.
Stones		..	..	..	..	..
Fine gravel		..	..	..	..	..
Coarse sand	per cent.	48·0	51·7	53·5	52·7	92·0
Fine sand	,,	28·1	31·0	34·4	38·8	6·7
Silt	,,	6·5	3·5	2·8	1·8	0·0
Clay	,,	8·8	5·8	5·2	5·7	2·5
$CaCO_3$	,,	..	..	..	..	..
Loss on solution	,,	1·97	2·13	1·55	0·45	0·23
Moisture	,,	1·65	2·33	1·53	0·60	0·15
Loss on ignition	,,	8·68	7·43	4·48	2·18	0·70
Exchangeable CaO	,,	0·087	0·106	0·038	0·009	0·001
pH		4·85	5·15	5·00	4·81	4·89
Composition of the clay fraction						
SiO_2	per cent.	44·38	30·66	34·76	38·55	40·40
Fe_2O_3	,,	12·31	21·65	19·96	18·16	19·07
Al_2O_3	,,	31·39	32·95	36·18	34·03	32·77
TiO_2	,,	0·38	0·55	0·86	0·74	0·86
SiO_2/R_2O_3		1·92	1·11	1·21	1·43	1·53
SiO_2/Al_2O_3		2·40	1·58	1·63	1·92	2·09
SiO_2/Fe_2O_3		9·57	3·77	4·63	5·65	5·63

have little effect on plant-life. This distance usually varies from 3 to 6 feet. In the method adopted for describing the thickness of the horizons in the profile-descriptions, due allowance must be made for the fact that variations occur from place to place.

Analytical Data

Each series has been sampled at typically representative places over the area. Sampling is invariably carried out by digging a hole with a spade, no other method having proved satisfactory. Permanent samples of each horizon are retained and analysed. On each sample the mechanical analysis (by the International Method) loss on ignition, and the exchangeable calcium or, alternatively, the free lime have been determined. In addition, the organic carbon and nitrogen have been estimated on a limited number. In each of the more important series the ferric, aluminium, titanium oxides, and the silica content have been determined in the clay from each horizon.

These data are particularly useful in determining the changes that have occurred in the parent material as a result of soil-forming processes.

Area and Extent of the Series

The area of each of the series has been measured on each 6-inch map over the whole area. The information derived shows up the relative importance of each series. It is highly desirable that in the future experimental work should be carried out on each of the more important series, and for this purpose a scheme based on a long-range policy is needed.

In the following table the area of each series is expressed as a percentage of the total area (122,880 acres):

Newport	20·06	Peaty loam	2·26	Worcester	0·76
Salop	13·99	Clive	2·14	Strine	0·66
Bridgnorth	12·07	Alluvium	2·02	Shifnal	0·63
Baschurch	7·26	Aber	1·92	Albrighton	0·51
Crannymoor	7·07	Hodnet	1·36	Leaton	0·11
Cegin	6·06	Conway	1·25	Goldstone	0·16
Roden	5·95	Brockhurst	1·04	Whittington	0·24
Peat	5·82	Hoo	0·85	Haughmond	0·06
Wem	3·84	Lilleshall	0·84	Unnamed series, water, &c.	1·08

DESCRIPTION OF SERIES

Soils falling within the Podsolic Group. Podsols and Brown Earth

Goldstone Series. Podsol (Plate 12, Fig. 1). Table 1.

Parent material: Bunter pebble beds.
Topography: Flat to gently undulating.
Drainage: Free to excessive.
Vegetation: Heath. *Quercus* (scrub), *Betula, Vaccinium, Erica, Calluna, Rubus, Festuca.*

TABLE 3

		0–12 in.	12–16 in.	16–28 in.
Stones		..	..	..
Fine gravel		..	..	..
Coarse sand	per cent.	70·9	72·5	83·1
Fine sand	,,	12·8	15·2	9·1
Silt	,,	10·7	7·7	10·7
Clay	,,	1·5	1·5	1·2
$CaCO_3$	,,	..	..	..
Loss on solution	,,	0·94	0·62	0·36
Moisture	,,	0·78	0·58	0·43
Loss on ignition	,,	2·67	1·72	1·15
Exchangeable CaO	,,	0·193	0·125	0·091
C	,,	1·92	0·45	0·28
N	,,	0·21	0·05	0·05
C/N ratio		9·16	9·88	5·60
pH		6·26	5·88	6·64
Composition of the clay fraction				
SiO_2	per cent.	48·24	49·24	48·56
Fe_2O_3	,,	10·05	10·15	10·05
Al_2O_3	,,	29·25	28·19	31·34
TiO_2	,,	0·70	0·76	0·76
SiO_2/R_2O_3		2·29	2·41	2·18
SiO_2/Al_2O_3		2·62	2·96	2·63
SiO_2/Fe_2O_3		12·76	12·90	12·85

TABLE 4

		0–9 in.	9–18 in.	Below 18 in.
Stones		..	..	..
Fine gravel		..	..	..
Coarse sand	per cent.	35·9	36·5	39·6
Fine sand	,,	31·1	31·6	35·5
Silt	,,	12·0	13·0	8·8
Clay	,,	16·3	17·5	15·3
$CaCO_3$	,,	..	..	..
Loss on solution	,,	0·66	0·47	0·37
Moisture	,,	0·90	1·13	0·53
Loss on ignition	,,	4·95	3·28	3·00
Exchangeable CaO	,,	0·036	0·042	0·049
pH		4·77	5·10	5·34
Composition of the clay fraction				
SiO_2	per cent.	48·17	47·78	47·76
Fe_2O_3	,,	9·55	11·03	11·52
Al_2O_3	,,	33·51	32·73	31·86
TiO_2	,,	0·82	0·82	0·90
SiO_2/R_2O_3		2·06	2·04	2·07
SiO_2/Al_2O_3		2·44	2·48	2·54
SiO_2/Fe_2O_3		13·42	11·52	11·03

Profile:

A_0	0–6 in.	Leaf mould.
	6–9 in.	Greyish-black, humified organic matter. Bleached sand grains, numerous pebbles.
A_1	9–19 in.	Pale grey, loose sand with bleached grains. Numerous pebbles free from iron-oxide stain.
B_1	19–23 in.	Compact humified organic matter.
B_2	23–35 in.	Compact cinnamon-yellow light sand with numerous stained pebbles. Decreasing intensity of coloration with depth. Upper surface consists of a $\frac{1}{4}$ in. layer of cemented and lustrous iron oxide.
C	Below 35 in.	Pebbly brownish-red laminated and friable sandy rock.

Crannymoor Series. Podsol (Plate 12, Fig. 2). TABLE 2.

Parent material: Red and yellow sands of Triassic, glacial or alluvial origins.
Topography: Flat and gently undulating.
Drainage: Free.
Vegetation: Heath (as Goldstone) or reclaimed heath bearing agricultural crops.

Profile:

A_0 & A_1	0–8 in.	Loose, black, light humus-sand. Bleached grains.
B_1	8–11 in.	Black humus-sand hard and compact.
B_2	11–18 in.	Dark coffee-brown, light sand. Hard and compact.
	18–34 in.	Ochreous-brown, light sand with little or no humus.
C	Below 34 in.	Pale pinkish, loose, light sand.

As a result of cultivation this profile does not show the clear-cut features in the A, B, and C horizons occurring in the Goldstone Series.

Bridgnorth Series. Brown earth (Plate 12, Fig. 3). TABLE 3.

Parent material: Bunter Sandstone.
Topography: Elevated and sloping.
Drainage: Free.
Vegetation: Usually cultivated.

Profile:

0–12 in. Dark greyish-brown, medium-grained, light sand. Stoneless or nearly so.
12–16 in. Pale brownish-red, light sand gradually merging into brownish-red sandstone.
16–28 in. Weathered sandstone rock. Loose and friable.
28 in.+Unweathered rock.
Range of types: Light sand, loamy sand.

Shifnal Series. Brown earth. TABLE 4.

Parent material: Keele or Enville Sandstone (with marl bands).
Topography: Elevated and sloping.
Drainage: Free.
Vegetation: Cultivated crops and grassland.

TABLE 5

		0–6 in.	*6–15 in.*	*15–36 in.*
Stones		..	..	..
Fine gravel		..	..	..
Coarse sand	per cent.	8·9	10·4	3·5
Fine sand	,,	51·6	56·5	29·0
Silt	,,	13·5	13·8	29·0
Clay	,,	21·0	17·8	34·8
$CaCO_3$	,,	..	..	..
Loss on solution	,,	1·21	1·04	0·86
Moisture	,,	1·45	1·10	2·50
Loss on ignition	,,	6·73	4·20	5·40
Exchangeable CaO	,,	0·100	0·104	0·193
pH		5·20	5·45	5·86
Composition of the clay fraction				
SiO_2	per cent.	47·62	48·22	50·47
Fe_2O_3	,,	10·27	10·67	24·01
Al_2O_3	,,	29·72	28·20	11·60
TiO_2	,,	0·71	0·76	0·79
SiO_2/R_2O_3		2·23	2·34	2·73
SiO_2/Al_2O_3		2·72	2·90	3·57
SiO_2/Fe_2O_3		12·33	12·01	11·57

TABLE 6

		0–8 in.	*8–14 in.*	*14–20 in.*	*Below 20 in.*
Stones	per cent.	5·7	13·3	14·0	10·8
Fine gravel	,,	0·9	1·1	1·3	3·0
Coarse sand	,,	44·4	47·3	49·0	58·0
Fine sand	,,	28·0	31·2	35·5	34·0
Silt	,,	10·0	9·0	8·0	3·3
Clay	,,	15·8	13·0	8·3	6·0
$CaCO_3$	,,	0·06	..	..	..
Loss on solution	,,	1·60	1·34	1·19	0·17
Moisture	,,	0·93	0·73	0·53	0·28
Loss on ignition	,,	4·18	2·70	2·03	1·33
Exchangeable CaO	,,	0·507	0·100	0·073	0·039
pH		7·08	6·81	6·69	6·63
Composition of the clay fraction					
SiO_2	per cent.	47·25	46·54	44·14	44·32
Fe_2O_3	,,	9·92	10·51	10·21	9·92
Al_2O_3	,,	29·80	29·23	31·87	34·50
TiO_2	,,	0·81	0·91	0·77	0·81
SiO_2/R_2O_3		2·22	2·20	1·95	1·84
SiO_2/Al_2O_3		2·69	2·70	2·35	2·18
SiO_2/Fe_2O_3		12·67	11·78	11·50	11·88

TABLE 7

		0–10 in.	*10–16 in.*	*16–20 in.*	*Below 20 in.*
Stones	per cent.	6·8	..	..	..
Fine gravel	,,	0·7	..	..	..
Coarse sand	,,	33·4	22·5	49·8	16·0
Fine sand	,,	29·6	18·1	16·9	15·0
Silt	,,	15·0	14·3	13·0	29·5
Clay	,,	16·8	33·8	18·0	37·0
$CaCO_3$	,,	..	..	..	..
Loss on solution	,,	1·35	0·85	0·69	0·91
Moisture	,,	1·54	2·24	1·14	2·20
Loss on ignition	,,	4·12	3·84	2·59	3·69
Exchangeable CaO	,,	0·145	0·133	0·103	0·157
pH		7·3	7·6	8·0	7·68
Composition of the clay fraction					
SiO_2	per cent.	47·98	46·79	47·48	49·27
Fe_2O_3	,,	10·32	11·19	12·72	8·03
Al_2O_3	,,	30·81	30·30	31·28	28·95
TiO_2	,,	0·65	0·49	0·50	0·77
SiO_2/R_2O_3		2·18	2·12	2·04	2·45
SiO_2/Al_2O_3		2·64	2·62	2·57	2·89
SiO_2/Fe_2O_3		12·37	11·13	9·93	16·32

TABLE 8

		0–9 in.	*9–14 in.*
Stones	per cent.	17·0	..
Fine gravel	,,	7·7	..
Coarse sand	,,	24·9	26·7
Fine sand	,,	31·3	32·5
Silt	,,	17·8	16·5
Clay	,,	18·3	19·0
$CaCO_3$	,,	..	..
Loss on solution	,,	1·67	2·54
Moisture	,,	2·95	2·68
Loss on ignition	,,	10·20	7·40
Exchangeable CaO	,,	0·173	0·181
pH		5·78	6·15
Composition of the clay fraction			
SiO_2	per cent.	45·43	45·75
Fe_2O_3	,,	10·40	10·83
Al_2O_3	,,	32·20	30·97
TiO_2	,,	0·60	0·65
SiO_2/R_2O_3		1·99	2·00
SiO_2/Al_2O_3		2·39	2·55
SiO_2/Fe_2O_3		11·62	11·24

Profile:
0–9 in. Brownish-red, loamy sand. Crumbly and somewhat gravelly.
9–18 in. Similar material, but rather more compact. Gravelly.
Below 18 in. Disintegrated lavender sandstone, passing into a layer of purplish-red marl at 40 in.
Range of types: Loamy sand, sandy loam.

Hodnet Series. Brown earth. TABLE 5.
Parent material: Keuper Sandstone (Waterstones) with bands of marl alternating.
Topography: Elevated and sloping.
Drainage: Free.
Vegetation: Cultivated crops, grassland, and woodland.
Profile:
0–6 in. Dark brown, loamy sand. Fine to medium-grained. Occasional pebbles, indistinctly passing into layer below.
6–15 in. Brown, loamy sand, fine to medium-grained.
16–36 in. Purplish-brown, heavy loam. Granular structure and including a few pin-head nodules of micaceous fine sand.
Range of types: Loamy sand, sandy loam.

Newport Series. Brown earth. TABLE 6.
Parent material: Triassic, glacial, or fluvio-glacial sand and gravels.
Topography: Sloping and undulating, frequently in mounds.
Drainage: Free, sometimes to excess.
Profile:
0–8 in. (8 in.). Greyish-brown, loamy sand, medium-grained and moderately pebbly.
8–14 in. (6 in.). Pale brown (sometimes loamy), light sand. Pebbly and containing less humus than the top layer.
14–20 in. (6 in.). Brown, gritty, light sand with numerous pebbles.
Below 20 in. Pinkish pale brown, gritty, light sand, somewhat pebbly.
Range of types: Light sand, loamy sand, humus sand.

Lilleshall Series. Brown earth. TABLE 7.
Parent material: Upper Coal Measures. Keele and Enville Beds.
Topography: Gently sloping.
Drainage: Usually free.
Vegetation: Under cultivation.
Profile:
0–10 in. Brownish-red, sandy, light loam. Some stones and gravel.
10–16 in. Band of yellowish-red, very compact, tenacious clay.
16–20 in. Dark purple, weathered, sand rock, crumbly and alternating with the heavy material above and below.
20 in.+ Yellowish-red clay.
Range of types:[1] Loamy sand, sandy loam, medium loam, heavy loam.

[1] The number of types in this series has been increased from one in Pt. I to four as a result of further field work.

Haughmond Series. Brown earth under cultivation. TABLE 8.

Parent material: Pre-cambrian. Longmyndian sandstones.
Topography: Elevated and sloping.
Drainage: Usually free. Excessive on steeper slopes.
Vegetation: Partly under woodland and partly under cultivation and grass.

Profile:

0–9 in. Dark greyish-brown, fine, sandy, light loam. Stony.
9–14 in. Paler brown, fine-grained, sandy loam. Very stony.
14 in.+ Longmyndian rock.

Baschurch Series. Brown earth (Plate 13, Fig. 4). TABLE 9.

Parent material: Mixture of Welsh and Northern (Triassic) light glacial drift. Pebbles mainly composed of Palaeozoic shale material with granites, quartzites, &c., of Northern origin.
Topography: Gently undulating.
Drainage: Free.
Vegetation: Usually cultivated.

Profile:

0–8 in. Dark greyish-brown, sandy and gritty light loam. Crumb structure. Many pebbles of Welsh and Northern origin.
8–36 in. Paler brown sandy and gritty light loam rather more friable than top layer. Pebbly.
36 in. Similar material.
Range of types: Light sand, loamy sand, light loam, and silty light loam.

Clive Series. Brown earth. TABLE 10.

Parent material: Trias. Grinshill and Ruyton sandstones.
Topography: Elevated and sloping.
Drainage: Free.
Vegetation: Cultivated crops.

Profile:

0–8 in. Dark brown medium to coarse-grained loamy sand. Occasional pebbles.
8–26 in. Coffee-brown medium to coarse-grained light sand. Loose. Some gravel and pebbles. Occasional crumbling pebbles of yellow sandstone.
23–36 in. Similar material but containing more yellow-sandstone nodules especially towards the base. Streaks of finely divided manganese dioxide occur in the lower part of this horizon.
36–48 in. Gradual transition to yellow-sandstone rock with streaks of manganese dioxide.
48 in.+ Hard, yellow sandstone with medium to coarse grains.
Range of types: Light sand, loamy sand, and sandy loam.

TABLE 9

		0–8 in.	*Below 8 in.*
Stones	per cent.	25·0	35·0
Fine gravel	,,	1·5	1·5
Coarse sand	,,	38·2	41·1
Fine sand	,,	27·4	26·5
Silt	,,	14·8	13·3
Clay	,,	14·8	14·5
$CaCO_3$	,,	0·40	0·24
Loss on solution	,,	2·00	1·63
Moisture	,,	1·15	2·80
Loss on ignition	,,	5·60	4·40
Exchangeable CaO	,,	0·775	0·589
pH		7·63	7·65
Composition of the clay fraction			
SiO_2	per cent.	44·76	43·58
Fe_2O_3	,,	11·98	13·27
Al_2O_3	,,	33·43	33·30
TiO_2	,,	0·77	0·80
SiO_2/R_2O_3		1·85	1·77
SiO_2/Al_2O_3		2·27	2·22
SiO_2/Fe_2O_3		9·94	8·73

TABLE 10

		0–8 in.	*8–26 in.*	*26–36 in.*	*36–48 in.*	*Below 48 in.*
Stones Fine gravel	per cent.	3·0	3·0	..	..	..
Coarse sand	,,	29·7	28·6	25·4	24·4	36·4
Fine sand	,,	45·5	51·8	65·9	68·3	58·0
Silt	,,	8·5	6·5	1·8	2·3	1·0
Clay	,,	12·5	11·0	6·3	5·3	4·0
$CaCO_3$	,,	..	..	..	..	1·66
Loss on solution	,,	1·76	1·52	1·76	1·62	1·46
Moisture	,,	1·60	0·65	0·60	0·50	0·13
Loss on ignition	,,	3·88	2·60	1·50	1·35	1·75
Exchangeable CaO	,,	0·111	0·115	0·100	0·275	Free $CaCO_3$
pH		5·6	6·2	6·4	6·8	..
Composition of the clay fraction						
SiO_2	per cent.	47·52	46·35	43·55	44·60	47·85
Fe_2O_3	,,	11·60	12·70	18·60	18·10	15·10
Al_2O_3	,,	29·47	28·96	23·70	23·21	22·28
TiO_2	,,	0·70	0·80	0·55	0·50	0·48
MnO_2	,,	1·23	2·04	4·79	3·06	0·53
SiO_2/R_2O_3		2·19	2·12	2·08	2·18	2·54
SiO_2/Al_2O_3		2·70	2·83	3·12	3·26	3·64
SiO_2/Fe_2O_3		10·89	9·71	6·23	6·55	8·43

TABLE 11

		0–3 in.	*3–7 in.*	*7–30 in.*	*Below 30 in.*
Stones		..	..	..	..
Fine gravel		..	..	..	..
Coarse sand	per cent.	21·7	22·4	19·1	18·7
Fine sand	,,	53·7	53·2	67·6	75·0
Silt	,,	8·8	9·3	5·8	3·0
Clay	,,	10·0	11·0	8·0	5·0
$CaCO_3$	,,	..	..	..	..
Loss on solution	,,	1·38	1·28	0·58	0·30
Moisture	,,	1·70	1·00	0·40	0·30
Loss on ignition	,,	7·15	3·60	1·70	1·05
Exchangeable CaO	,,	0·029	0·009	0·007	0·002
pH		4·51	4·40	4·45	4·54
Composition of the clay fraction					
SiO_2	per cent.	41·15	42·11	40·60	41·09
Fe_2O_3	,,	16·14	16·04	14·95	13·66
Al_2O_3	,,	32·96	32·68	34·47	31·47
TiO_2	,,	0·90	0·88	0·88	0·81
SiO_2/R_2O_3		1·61	1·66	1·56	1·74
SiO_2/Al_2O_3		2·12	2·19	2·00	2·21
SiO_2/Fe_2O_3		6·83	6·98	7·22	8·00

TABLE 12

		0–9 in.	*9–27 in.*
Stones	per cent.	2·8	2·5
Fine gravel	,,	..	..
Coarse sand	,,	7·9	4·9
Fine sand	,,	26·3	11·4
Silt	,,	28·8	35·0
Clay	,,	28·3	42·5
$CaCO_3$	,,	0·07	..
Loss on solution	,,	1·98	1·20
Moisture	,,	3·30	2·05
Loss on ignition	,,	9·30	5·60
Exchangeable CaO	,,	0·987	0·251
pH		6·73	7·28
Composition of the clay fraction			
SiO_2	per cent.	46·95	47·11
Fe_2O_3	,,	6·18	9·90
Al_2O_3	,,	34·70	32·62
TiO_2	,,	0·73	0·93
SiO_2/R_2O_3		2·06	2·05
SiO_2/Al_2O_3		2·30	2·45
SiO_2/Fe_2O_3		20·41	12·66

Leaton Series. Probably eroded podsol. TABLE 11.

Parent material: Probably terrace of Triassic origin, free from pebbles.
Topography: Sloping and steeply sloping.
Drainage: Free.
Vegetation: Deciduous woodland.

Profile:

0–3 in. Greyish-black, humus-sand with bleached grains and covered with thin leaf-litter.
3–7 in. Compact yellowish-brown, medium-grained, light sand.
7–30 in. Similar material but less compact.
30 in.+ Compact pinkish-brown, light sand.
Range of types: Light sand.

SERIES FALLING WITHIN THE GROUND-WATER OR MEADOW-SOILS GROUP AND PEAT SOILS

Cegin Series. Meadow soil. TABLE 12.

Parent material: Heavy boulder clay of Welsh origin and mainly derived from Palaeozoic mudstones.
Topography: Flat to gently undulating.
Drainage: Impeded, due to presence of impervious layers.
Vegetation: Usually under grass.

Profile:

0–9 in. Dark brownish-grey, fine, sandy, heavy silt-loam. Rusty mottlings frequently present following the grass roots. A few pebbles. Added calcium carbonate.
9–27 in. Light brownish-grey silty clay with much pale bluish-grey, orange and black mottlings. Few pebbles.
27 in. Dull brown silty clay with less mottling than in previous horizon.
Range of types: Light loam, silty light loam, silty loam, heavy loam, silty heavy loam, sandy silt-loam, silty clay.

Conway Series. Meadow soil. TABLE 13.

Parent material: Alluvium (R. Severn) mostly derived from Palaeozoic mudstones.
Topography: Flat to gently undulating.
Drainage: Impeded. Somewhat variable.
Vegetation: Grassland.

Profile:

0–10 in. Pale greyish-brown, fine, sandy, medium or heavy silt-loam. Stoneless. Slight rusty mottlings tending to follow the grass roots. Rather compact, crumbling with pressure.
10–16 in. Pale grey, heavy silt-loam with orange and some black mottlings. Compact.
16 in.+ Similar material with more pale grey and black mottlings. Less pronounced orange mottling.
Range of types: Medium silt-loam, heavy silt-loam.

TABLE 13

		0–10 in.	*10–16 in.*	*Below 16 in.*
Stones / Fine gravel	per cent.	1·0	..	..
Coarse sand	,,	5·7	2·2	1·2
Fine sand	,,	13·2	8·7	4·4
Silt	,,	35·0	40·8	44·5
Clay	,,	35·0	43·3	43·7
$CaCO_3$	,,	1·02	0·23	0·05
Loss on solution	,,	3·10	1·50	1·63
Moisture	,,	2·10	2·20	2·05
Loss on ignition	,,	9·75	6·45	6·25
Exchangeable CaO	,,	Free $CaCO_3$	..	..
pH		7·85	7·90	7·95
Composition of the clay fraction				
SiO_2	per cent.	47·30	47·39	47·76
Fe_2O_3	,,	9·14	10·04	8·35
Al_2O_3	,,	32·72	33·77	32·75
TiO_2	,,	0·87	0·92	0·90
SiO_2/R_2O_3		2·08	2·00	2·13
SiO_2/Al_2O_3		2·45	2·35	2·47
SiO_2/Fe_2O_3		13·77	12·59	15·21

TABLE 14

		0–5 in.	*5–10 in.*	*Below 10 in.*
Stones		..	..	..
Fine gravel		..	..	..
Coarse sand	per cent.	18·9	21·2	20·2
Fine sand	,,	29·3	31·9	29·7
Silt	,,	25·0	25·0	30·8
Clay	,,	21·3	20·0	18·0
$CaCO_3$	,,	..	..	..
Loss on solution	,,	1·45	0·98	0·65
Moisture	,,	1·60	1·45	1·30
Loss on ignition	,,	6·05	5·00	4·23
Exchangeable CaO	,,	0·206	0·193	0·157
pH		6·07	6·07	6·35
Composition of the clay fraction				
SiO_2	per cent.	46·43	47·01	46·24
Fe_2O_3	,,	9·70	9·70	10·20
Al_2O_3	,,	32·79	32·48	32·56
TiO_2	,,	1·06	1·07	1·04
SiO_2/R_2O_3		2·02	2·06	2·01
SiO_2/Al_2O_3		2·40	2·46	2·41
SiO_2/Fe_2O_3		12·73	12·89	12·06

Albrighton Series. Meadow soil. TABLE 14.

Parent material: Mainly Welsh boulder clay derived from shale, and fine-grained grits.
Topography: Slightly elevated and sloping.
Drainage: Impeded.
Vegetation: Arable and grassland.

Profile:

0–5 in. Greyish-brown, fine, sandy (gritty) silt-loam. Many stones, mostly of Welsh origin. Compact cloddy structure.
5–10 in. Paler-coloured material similar in texture to previous horizon with more stones and rather more compact.
10 in.+ Grey, fine-sandy silt with orange mottling. Stony and gritty. Very compact. This is the layer mainly causing impedance.
Range of types: Light loam, silty light loam, silty loam, light silt and medium silt.

Worcester Series. Meadow soil. TABLE 15.

Parent material: Keuper Marl.
Topography: Elevated and sloping.
Drainage: Impeded but variable.
Vegetation: Usually grassland.

Profile:

0–12 in. Dark brown loam with some medium-sized sand grains.
12–15 in. Paler brown to reddish-brown, medium-grained loam.
15–30 in. Dull reddish-brown, heavy, loam or clay. Much black mottling with manganese dioxide in the upper part of this horizon. Crystals of calcium sulphate present.
30 in.+ Similar materials with less black mottling.
Range of types: Medium loam.

Salop Series.[1] Meadow soil. TABLE 16.

Parent material: Heavy Triassic boulder clay.
Topography: Gently sloping to flat.
Drainage: Impeded.
Vegetation: Mainly grassland.

Profile:

0–10 in. Greyish-brown medium loam. Rusty streaks following grass roots. Nearly stoneless.
10–18 in. Paler brown heavy loam with orange mottling (maximum mottling at 16 in. depth).
18–36 in. Chocolate-brown to brown clay, mottled pale blue and black to a distance of three feet. Grass roots penetrate to this layer. Clay is highly plastic and weathered in fissures down to several feet.
Range of types: Light loam, loam, heavy loam, and clay.

[1] This series name was unfortunately omitted from the list on p. 187 in Pt. I. It should be included as: Red marls—Drift—Salop (4).

TABLE 15

		0–12 in.	*12–15 in.*	*15–30 in.*	*Below 30 in.*
Stones					
Fine gravel	per cent.	1·7	1·7	..	..
Coarse sand	,,	13·2	12·6	1·1	3·5
Fine sand	,,	39·7	34·0	10·5	9·3
Silt	,,	15·8	24·8	31·5	31·3
Clay	,,	27·5	26·8	50·5	38·5
$CaCO_3$	,,	..	..	2·75	16·82
Loss on solution	,,	1·31	1·00	1·38	2·03
Moisture	,,	1·50	1·05	2·90	3·40
Loss on ignition	,,	5·85	4·80	6·90	11·48
Exchangeable CaO	,,	0·273	0·289	Free $CaCO_3$	Free $CaCO_3$
pH		5·6	6·6	..	..
Composition of the clay fraction					
SiO_2	per cent.	49·26	49·36	49·18	49·29
Fe_2O_3	,,	10·55	10·55	10·45	10·55
Al_1O_3	,,	27·08	25·26	24·20	24·19
TiO_2	,,	0·82	0·82	0·85	0·86
SiO_2/R_2O_3		2·47	2·62	2·70	2·71
SiO_2/Al_2O_3		3·08	3·31	3·45	3·46
SiO_2/Fe_2O_3		12·42	12·44	12·51	12·43

TABLE 16

		0–10 in.	*10–18 in.*	*18–36 in.*
Stones		..	..	..
Fine gravel		..	..	..
Coarse sand	per cent.	17·8	16·1	2·9
Fine sand	,,	16·0	9·4	2·1
Silt	,,	25·8	25·3	22·3
Clay	,,	33·5	46·5	64·0
$CaCO_3$	,,	..	..	..
Loss on solution	,,	2·93	1·90	1·01
Moisture	,,	5·35	2·50	3·97
Loss on ignition	,,	11·55	5·54	6·00
Exchangeable CaO	,,	0·161	0·126	0·155
pH		6·06	7·29	7·68
Composition of the clay fraction				
SiO_2	per cent.	48·50	47·16	46·72
Fe_2O_3	,,	11·78	9·72	10·80
Al_2O_3	,,	30·90	30·13	29·30
TiO_2	,,	0·65	0·65	0·80
SiO_2/R_2O_3		2·14	2·20	2·19
SiO_2/Al_2O_3		2·66	2·66	2·70
SiO_2/Fe_2O_3		10·95	12·90	11·50

Wem Series. Meadow soil. TABLE 17.

Parent material: Sandy boulder-clay mixture of Triassic origin with sandy overwash.
Topography: Flat and gently undulating.
Drainage: Impeded.
Vegetation: Arable and grassland.

Profile:

0–12 in. Dark grey, loamy sand with bleached, medium-sized grains. Loose and somewhat stony.

12–21 in. Pale brown to fawn, wettish, loamy sand. Rusty mottling with nodular deposits of iron oxide.

21 in.+ Reddish-brown, sandy clay with pale brown mottlings. Below 30 in. this layer becomes more uniform in colour and texture.

Range of types: Light sand, loamy sand, light loam.

Roden Series. Meadow soil. TABLE 18.

Parent material: Sandy down-wash over glacial drift clay of Triassic origin.
Topography: Gently sloping.
Drainage: Somewhat impeded.
Vegetation: Arable and grassland.

Profile:

0–22 in. Reddish-brown, loamy sand derived from colluvial Bunter-Sandstone soil or sandy drift.

22–25 in. Reddish-brown, heavy loam.

25 in.+ Chocolate-brown clay with blue mottlings.

Range of types: Light sand and loamy sand.

Aber Series. Meadow soil. TABLE 19.

Parent material: Welsh glacial drift over Triassic boulder clay.
Topography: Slightly elevated and gently undulating.
Drainage: Impeded.
Vegetation: Usually grassland.

Profile:

0–10 in. Greyish-brown, fine, sandy, silty, light loam containing a few rounded and shaly pebbles. Rusty mottlings following the grass roots.

10–20 in. Pale brown medium to fine-grained sandy light loam with rusty and orange mottlings. Slightly pebbly.

20–27 in. Mottled clay-sand and sandy clay. Generally brown but with considerable grey, orange, rusty, and black mottlings. Somewhat pebbly. Layer of transition between the Welsh and Northern drifts.

27 in.+ Brown Northern (Triassic) boulder clay (containing some sand) with grey and orange mottlings. Becoming more uniform in colour with increasing depth.

Range of types: Light loam, silty light loam, medium loam, silty medium loam, heavy loam.

TABLE 17

		0–12 in.	*12–21 in.*	*Below 21 in.*
Stones	per cent.	6·2	15·1	..
Fine gravel	,,	..	1·3	..
Coarse sand	,,	26·7	32·9	20·0
Fine sand	,,	37·7	42·2	40·9
Silt	,,	14·8	12·8	13·5
Clay	,,	16·5	11·0	25·3
$CaCO_3$	,,	..	..	..
Loss on solution	,,	1·35	0·94	1·24
Moisture	,,	1·28	1·15	1·08
Loss on ignition	,,	5·03	2·85	3·15
Exchangeable CaO	,,	0·128	0·061	0·075
pH		5·66	5·80	6·30
Composition of the clay fraction				
SiO_2	per cent.	49·44	48·32	49·00
Fe_2O_3	,,	8·36	10·45	12·14
Al_2O_3	,,	30·89	30·87	27·02
TiO_2	,,	0·90	1·08	0·87
SiO_2/R_2O_3		2·32	2·18	2·39
SiO_2/Al_2O_3		2·71	2·66	3·08
SiO_2/Fe_2O_3		15·73	12·29	10·74

TABLE 18

		0–12 in.	*12–22 in.*	*22–25 in.*	*Below 25 in.*
Stones	per cent.	4·8	4·0	..	..
Fine gravel	,,	..	..	..	..
Coarse sand	,,	40·0	40·2	17·9	6·4
Fine sand	,,	30·7	30·8	26·5	7·6
Silt	,,	14·3	16·5	18·5	18·8
Clay	,,	12·3	12·0	33·7	63·5
$CaCO_3$	,,	..	..	..	..
Loss on solution	,,	1·28	0·95	1·03	1·14
Moisture	,,	1·10	1·10	2·01	3·61
Loss on ignition	,,	3·47	3·14	3·88	6·10
Exchangeable CaO	,,	0·147	0·145	0·147	0·219
pH		5·49	5·7	6·8	6·5

Composition of the clay fraction not determined.

Whittington Series. Meadow soil.

Parent material: Mixture of Welsh and Northern (Triassic) boulder clay.
Topography: Sloping.
Drainage: Impeded.
Vegetation: Arable and grassland.

Profile:
0–12 in. Grey sandy loam with few pebbles.
12–20 in. Very pale grey, bleached, loamy sand, with yellow and rusty mottlings. Water-holding horizon.
20 in.+ Pale whitish-grey clay-sand with rusty and yellow mottlings. Stoneless.
Range of types: Loamy sand and sandy loam.

Strine Series. Meadow soil. TABLE 20.

Parent material: Lacustrine laminated grey clay overlying thin band of sand and gravel over Triassic boulder clay.
Topography: Depressed. Ancient lake-bed now drained.
Drainage: Very impeded.
Vegetation: Grassland.

Profile:
0–10 in. Dark greyish-brown, heavy loam. Rusty mottling. Nearly stoneless. Crumb structure.
10–23 in. Bluish-grey silty clay, laminated and with ochreous, black (much manganese dioxide) and dark brown mottlings. Numerous grass roots in upper part.
23–24 in. Grey, bleached, coarse sand.
24–38 in. Brownish-red, gravelly, coarse sand, very loose, wet, and streaked (probably old root channels).
38 in.+ Chocolate-brown boulder clay with bluish and brown mottlings. Contains considerable amounts of plant-remains on surface.
Note on 23–24 in. horizon: Rather variable and ceases to exist at certain points examined.
Range of types: Light loam, medium loam, heavy loam, and clay.

Peat. Lowmoor. Fen type. TABLE 21.

Parent material: Mostly plant-remains.
Topography: Low-lying and depressed.
Drainage: Artificial. Naturally waterlogged.
Vegetation: Mostly grassland.

Profile:
0–8 in. Black, well-humified peat. A few bleached sand grains.
8–16 in. Brownish-black, semi-structural organic matter.
16–24 in. Paler brownish-black, rather more structural organic matter. Contains branches, twigs, leaves, &c.
24–30 in. Similar material.
30 in.+ Bleached sand.

TABLE 19

		0–10 in.	*10–20 in.*	*20–27 in.*	*Below 27 in.*
Stones	per cent.	1·5	6·1	5·0	5·6
Fine gravel	,,	..	..	..	..
Coarse sand	,,	16·9	17·3	16·5	13·7
Fine sand	,,	32·4	34·7	23·2	28·7
Silt	,,	21·3	23·0	27·5	26·3
Clay	,,	21·0	21·5	29·8	29·8
$CaCO_3$	,,	..	..	..	..
Loss on solution	,,	1·85	1·40	1·14	1·15
Moisture	,,	2·55	1·10	2·10	1·85
Loss on ignition	,,	8·55	4·65	4·20	3·95
Exchangeable CaO	,,	0·255	0·112	0·177	0·168
pH		5·95	6·58	5·85	6·29
Composition of the clay fraction					
SiO_2	per cent.	45·65	47·08	46·59	46·94
Fe_2O_3	,,	11·99	8·70	10·81	10·10
Al_2O_3	,,	33·70	33·00	33·02	31·06
TiO_2	,,	0·81	0·68	0·70	0·77
SiO_2/R_2O_3		1·72	2·07	1·98	2·12
SiO_2/Al_2O_3		2·30	2·42	2·39	2·56
SiO_2/Fe_2O_3		10·13	14·39	11·47	12·36

TABLE 20

		0–10 in.	*10–23 in.*	*23–24 in.*	*24–38 in.*	*Below 38 in.*
Stones	per cent.	..	..	13·0	20·0	..
Fine gravel	,,	..	..	1·3	2·3	..
Coarse sand	,,	7·4	2·9	55·7	40·4	3·7
Fine sand	,,	14·1	36·6	30·0	43·8	8·1
Silt	,,	14·0	15·8	3·3	3·3	17·5
Clay	,,	43·2	40·0	10·0	9·0	64·0
$CaCO_3$	,,	..	0·06	1·00	2·79	4·86
Loss on solution	,,	4·30	2·00	1·10	1·40	1·20
Moisture	,,	5·50	2·80	0·40	0·40	2·30
Loss on ignition	,,	20·95	6·05	2·45	2·90	8·75
Exchangeable CaO	,,	0·633		Free calcium carbonate.		
pH		5·42	8·00	7·77	8·50	7·70

Composition of the clay fraction not determined.

Mixed Alluvium. Meadow soil. TABLE 22.

Parent material: Alluvium.
Topography: Flat and depressed.
Drainage: Usually impeded.
Vegetation: Grassland.

Profile:

0–12 in. Brown light loam. Top three inches darker in colour with more humus. Rusty mottlings probably due to iron bacteria. Stoneless.

12–30 in. Peat. Almost entirely structural. Spongy and wet. Varies in colour from blackish-brown to pale brown.

30 in. Blackish-grey somewhat silty light loam containing much structural organic matter.

Range of types: Types undifferentiated, but extending from sands to silts and clays, and often peat.

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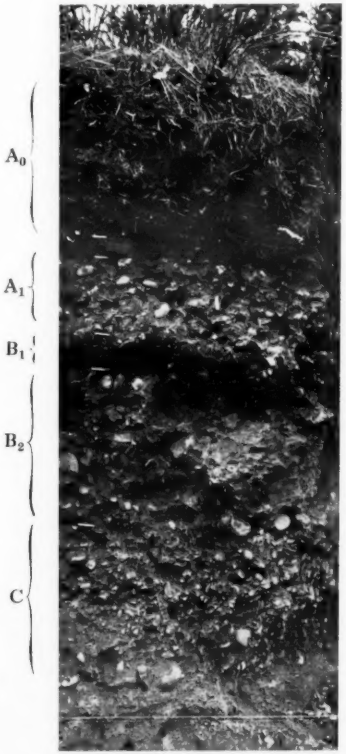
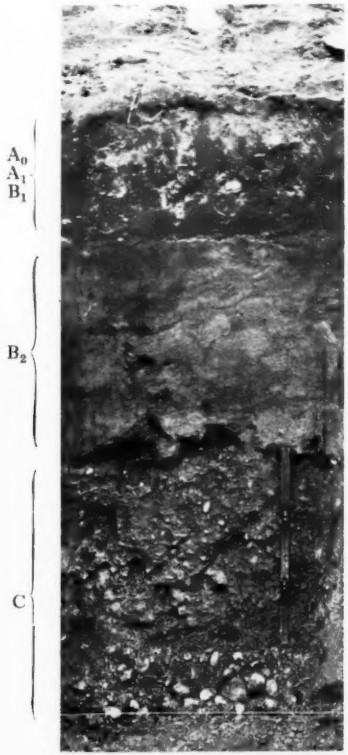


1. Podsol. Under Natural Heath Vegetation. Goldstone Series.



2. Podsol. Recently-reclaimed Heath under Cultivation. Crannymore Series.

3. Brown Earth. Old Enclosure under Cultivation. Bridgnorth Series.

EXAMPLES OF THREE TYPICAL SERIES DEVELOPED ON SIMILAR MATERIAL—RED BUNTER SANDSTONE

4. Brown Earth. Under Cultivation.
Baschurch Series.

PROFILE ON MIXED WELSH AND TRIAS DRIFT

TABLE 21

		0–8 in.	*8–16 in.*	*16–24 in.*	*24–30 in.*
Coarse sand	per cent.	14·2	4·9	12·7	20·2
Fine sand	,,	12·0	7·6	38·7	38·1
Silt	,,	5·5	11·5	4·5	5·8
Clay	,,	9·0	7·8	7·8	8·0
$CaCO_3$	,,	..	..	..	..
Loss on solution	,,	9·37	6·25	5·43	5·98
Moisture	,,	23·30	17·05	13·00	7·88
Loss on ignition	,,	37·85	56·73	37·48	32·23
Exchangeable CaO	,,	0·679	1·021	0·689	0·720
pH		5·77	5·87	5·68	5·20

Composition of the clay fraction not determined.

TABLE 22

		0–12 in.	*12–30 in.*	*Below 30 in.*
Coarse sand	per cent.	29·9	1·1	3·8
Fine sand	,,	28·3	9·1	34·9
Silt	,,	9·3	9·0	14·0
Clay	,,	22·0	14·8	24·8
$CaCO_3$	,,	..	..	..
Loss on solution	,,	2·88	6·70	3·80
Moisture	,,	2·78	22·83	6·35
Loss on ignition	,,	10·50	47·83	21·65
Exchangeable CaO	,,	0·220	0·755	0·433
pH		6·12	5·36	5·70

Composition of the clay fraction not determined.

YIELD, DURATION, AND DROUGHT-RESISTANCE OF LUCERNE AS INFLUENCED BY FREQUENCY AND TIME OF CUTTING

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THE problem of securing the most advantageous yield from a perennial forage crop is peculiarly subtle. It is not easy to suggest how a maximum yield may be obtained; and in addition to mere tonnage, several factors have to be considered, such as convenience of the farmer, seasonal requirements of the stock, digestibility of the fodder, and the influence of cutting upon future yields in the same year and upon the number of years that the crop may be expected to stand.

These requirements are to some extent antagonistic. It now seems probable that the most economic time to cut an established crop of lucerne either for hay or for green fodder so as to secure the best yield of a season is when the plants are in early bloom, when fresh shoots are breaking from the crown. Thornton and Nicol [1] recommended watching for the development of new shoots from the crown as the best indication of readiness for cutting. This recommendation was based upon the conclusions of many experimenters in the United States, but it was admitted that experimental evidence was then lacking for conditions in Great Britain (Woodman [2]). Even in the United States, where the lucerne crop has been most extensively studied, few experiments have been made to examine the effects of a season's cutting upon the yields of subsequent years; the majority of the experiments which have been performed upon the cutting of lucerne have considered digestibility together with bulk, obtainable in one year, usually after the seedling year. Very few records of experiments have been found by the author bearing directly on the effect of cutting in the year of sowing, and only a few others have been found in which the effects in subsequent years of cutting established lucerne were determined. Of these various publications, three are Scandinavian; and they appear to be little known. The language difficulty may therefore serve as the principal excuse for this review.

The problem of summarizing experiments upon the after-effects of cutting lucerne is made difficult by the necessity for distinguishing at least the year of sowing from later years. The diversity of cultural practices employed during the first few months of the crop leads to the subjection of crops of nominally the same age to very different influences, apart from cutting. Lucerne is sown at any time from spring to autumn, and when sown in spring and early summer it may be sown either on bare land or on land already occupied by a corn crop. It is not surprising that testimony to the utility and ease of management of lucerne should vary, since experimental evidence regarding the wisdom of any particular cultural practice or combination of practices is lacking. Thornton [3] was able to clear up one point when he showed that there was frequently

a benefit from inoculating lucerne seed when the crop was intended to be sown under a cereal. Regarding many other points in the cultivation of lucerne, there is no help but traditional experience varying over a wide range with but a relatively limited acreage of crop. Discussion of results is difficult in respect of cutting: two lucerne crops cut three months after sowing are differently fitted to stand the winter according as they had been sown in April or in June. Unfortunately, in the literature, details of the history of experimental crops are often insufficient.

I. *The Immediate Effects of Clipping: in the Season of Sowing*

Without attempting the operose task of carrying out field experiments to test all the possible combinations of conditions, Thornton and Nicol [4] devised a one-season's greenhouse experiment upon the effects of cutting of lucerne upon the roots of the plants. The results already published show that cutting (or rather its greenhouse equivalent, clipping) seedling lucerne twice, resulted in marked arrest of root-development. The total yield of dry matter and total nitrogen recovered in roots, standing tops, and clippings was not significantly affected by the two cuttings; the apparent net result of clipping was to transfer dry matter from root to top. The clippings were more nitrogenous, and therefore presumably less fibrous and more digestible, than the unclipped tops. A slightly larger yield of dry matter in tops was obtained by clipping than by allowing the lucerne to grow on. These advantages, however, were obtained wholly at the expense of the roots. Haselhoff, quoted by Walther [5], found the relation of root-mass to aerial part was 130 : 100 at beginning of bloom, but 218 : 100 at ripe-seed stage.

Thornton and Nicol made no attempt to determine the maximum number of cuts that might be taken. It should be borne in mind that the experiment was carried out under greenhouse conditions, which do not represent field conditions in our climate. Two clippings were made, and a third and later one might have been taken, if the experiment had been prolonged, but it was evident from the counts of nodules that by the end of August the plants were on the decline. This is not necessarily true under field conditions at that time of year, but the greenhouse conditions accelerated growth, and possibly August in the greenhouse might represent September in the field, so far as the age of the plants was concerned. At the beginning of the experiment, the greenhouse conditions were more favourable to growth than English field conditions. Hence in the experiment the lucerne could have been clipped twice with advantage to the yield of tops (though not the yield of root). Bearing in mind the difference in conditions, this experiment may be claimed to support the recommendation to cut spring-sown first-year lucerne only once. Even should the luxuriance of leafage of first-year lucerne tempt the grower to cut it twice, he should think of the check sustained by the roots when cut more than once, or too early in the season.

The experiment showed that the first-year lucerne clipped twice had at the end of August a slightly smaller weight of root than had unclipped lucerne a month earlier. In view of the results of this experiment, and in the light of remarks made in the preceding paragraph, it would seem

that under English farming conditions, spring-sown first-year lucerne, if cut once about August, would yield a large bulk of nutritious fodder without the plants' root-development receiving an undue check. There seems to be little need to fear that the lucerne in the field would become too stemmy if left uncut till fairly late in its first year. If cut too early, some bulk of forage would be lost and an early check would be given to root-development; the leaves of subsequent growth would fall off towards winter and be returned to the soil, but they would be more valuable as forage than as a top-dressing. Moreover, by later cutting the farmer would ensure a considerable gain in bulk of roots, which would have a more economic residual manurial value than would the leaves as top-dressing.

The basis of these conclusions has been broadened by the observations of other authors, who studied the effect of clipping or cutting lucerne in the field in its year of sowing. The valuable observations of McKee [6] have been quoted by Thornton and Nicol [4] and need not be given afresh here. McKee stated that he repeated in one year the work of a previous year on seedling lucerne, from which one deduces, without being quite certain, that the lucerne was sown afresh each year. He added a brief discussion of the effect of cutting upon yields in subsequent years. His experiments were made at Chico, California.

Sundelin and Franck [7] concluded from experiments in Sweden that lucerne should not be cut during the year of sowing. They sowed lucerne in mid-June in successive years and examined the effects upon the yield of two cuts in following years, of not cutting in the year of sowing, and of cutting about 61, 83, and 100 days after sowing. Marked depressions in yield followed after the later cuts, the effects, however, varying with season. Early cuttings in the year of sowing were made in August, and so enabled the plants to recover before winter. From the results of Sundelin and Franck it appears that the effects of cutting very young plants were largely offset when the plants were allowed to recuperate before the onset of winter. (Cf. Grandfield's results (Section III) on one-year-old plants.) In 1922 late autumn-cutting of newly sown lucerne prejudiced the yield for three years afterwards. In the case of lucerne sown in 1923, the cut whenever taken in that year severely depressed the yields of 1924 and 1925. The work of Sundelin and Franck further suggests the importance in Great Britain of sowing in spring if a cutting of economic size is desired in the year of sowing. Their plants cut in August, 61 days after sowing, were only 35–40 cm. high and had not reached the stage of beginning to bloom.

Two earlier observers recognized the harmful effects of cutting lucerne too harshly in its seedling year. Especially is careful management needful when it is wished to obtain a stand on types of land not thought to be particularly suitable for lucerne—as, for example, when lucerne is to be grown as a fire-break (Greenwood [8], Nicol [9]). In a short but valuable paper 'On the Growth of Lucerne on Thin Light Soils and Chalky Loams', Clayden [10], of Littlebury, suggested sowing lucerne (on such soils) 'about the second week in May *without any corn*. . . . If the season is favourable, the field will give a nice cut for the scythe at the end of

August or beginning of September, or else it may be fed with sheep or cattle; but it should not be depastured too closely.' Clayden added that on the soils of which he wrote lucerne would not yield its full crop to cutting until the third season. B[artholomew] Rocque, an eighteenth-century farmer at Walham Green, near London, wrote in the first edition of his book on lucerne [11]:

'In Languedoc they sow no Corn with it, and, when the Lucern is six or seven Inches high, they mow it; by which all the Seeds of annual Weeds are cut off and killed.'

The notion that early cutting of young lucerne somehow encouraged its vitality, and also had the beneficial effect of a fallow for suppressing weeds, persisted in the United States until the early years of the present century (for some quotations of typical opinions on these points, see McKee [6] and Graber *et al.* [12]). On very weedy ground, Cockayne [13] found that drastic cutting was the only practicable method of establishing a crop. Rocque, however, in the second edition [11] of his book, continued the above-quoted passage by the following:

'By my own Experience, I find they are in the wrong; for it bleeds it, so that the Plants make but little Progress when cut so young, and are a long time in recovering it. It ought never to be cut but when in Bloom.'

This is perspicacious, and suggests that Rocque made good use of the observations made in the four years which intervened between the editions of his book.

II. *The Effect of the Number of Times of Cutting Established Lucerne upon the Yields in Subsequent Years*

Hansen [14, 15] has published the results of two investigations on a field scale directed towards an examination of the effect of cutting lucerne a varying number of times in one year upon the crops in subsequent years. His work is little known and not easily available; also, it has not been well abstracted. Graphs summarizing some of his results obtained at Tystoft, Denmark [14] are reproduced below (Figs. 1 and 2). Hansen concluded that in established lucerne (not in its first year) three cuts per annum were necessary and sufficient. Unfortunately, his experiment gave no certain information upon the effects of cutting first-year lucerne, since his two fields were not comparably treated.

In Bornholm, Hansen [15] continued his continental Danish work by investigating the effects upon the following year's crop of cutting 2-year-old lucerne a varying number of times. A variety of treatments (inoculation, manuring, absence and presence of cover crop) were given upon 18 plots, but figures for the results of these treatments are not recorded. Each of the 18 plots was divided into four for cutting 1, 2, 3, and 4 times in one year (1908, 1910). In the following year (1909, 1911) each plot was cut three times. The results for a similar number of cuttings on each of the 18 plots appear to have been bulked, irrespective of manurial and other preliminary treatments. This is to be regretted, since data are scarce upon the effect of a cover crop upon a legume. The lucerne sown under a cover crop was not cut in the year of sowing, whilst the lucerne

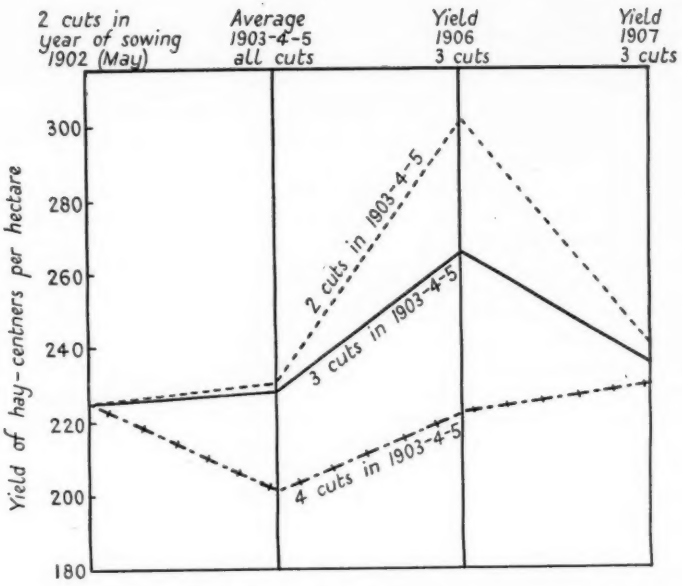

FIG. 1. Hansen's Tystoft data [14]. Varied number of mowings of spring-sown lucerne: yields in centners per hectare from Field I.

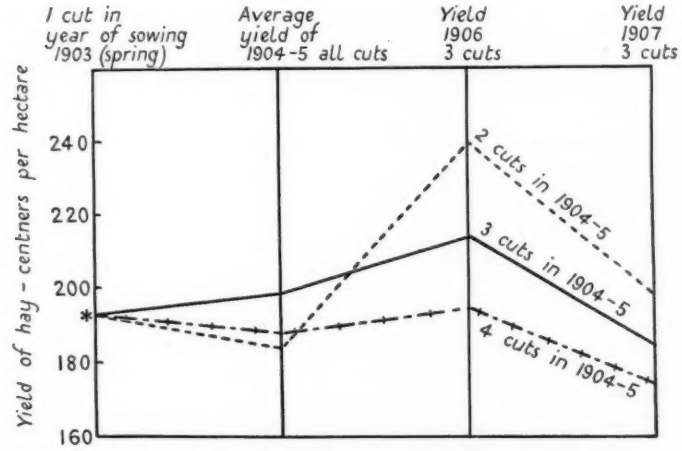

FIG. 2. Hansen's Tystoft data [14]. Varied number of mowings of spring-sown lucerne: yields in centners per hectare from Field II.

* This figure is not obtainable except from the corresponding graph in Hansen's paper, in the text of which it is stated that no weight for this cutting was recorded.

sown bare was cut once in September. Sowing was performed in May 1906. In 1907 all plots were cut twice (yields not recorded).

Hansen obtained his greatest yield over the period 1908–11, inclusive, by cutting once in 1908 and 1910 (8 cuts in all), but this result can be partly attributed to an unusually large yield in 1909. A steadier yield was given by cutting twice and three times in 1908 and 1910, whilst a marked reduction occurred throughout when four cuts were taken in those years. The striking fact emerges from his data that the total yield in each of the years 1908 and 1910 was hardly affected whether the lucerne was cut 1, 2, 3, or 4 times, but the reduction of yield in the following year increased with the frequency of cutting. It is probable that these reductions were really an expression of the adverse effects of late, rather than of too frequent cutting: Hansen's third cuts were taken in late August or late September, and his fourth cuts about October 10.

Hansen's results in Bornholm are summarized in Table 1.

TABLE 1

Data of Hansen's Experiments in Bornholm [15]

Effects of a varied and constant number of mowings in alternate years upon yields of 2-year-old spring-sown lucerne

A = number of cuts
B = annual yields of hay in centners per hectare

1908		*1909*		*1910*		*1911*		*Total*	
A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
1	198	3	339	1	189	3	230	8	955
2	189	3	254	2	187	3	196	10	825
3	190	3	228	3	225	3	174	12	818
4	172	3	174	4	196	3	132	14	674

III. *Effects of Cutting upon Thickness of Stand*

Several authors [10, 16, 17, 38] have found that in established lucerne the yield of each of a small number of cuts in any one year falls off rather gradually as the season advances, though this does not appear to hold in some South American countries. This decrease in top-growth seems to be a physiological expression of the balance between root-reserves and photosynthesis, which is disturbed at each cutting. In the experiments of Hill and Thomas (18) defoliation was effected by fumigation with sulphur dioxide as well as by clipping. The clipping experiment of Thornton and Nicol [4], though made with seedling lucerne, by its observations upon roots throws some light upon the effects of such disturbances. The time separating the last cut of one year and the first cut of the next year is much longer than the interval between successive cuts in one season. A consideration of these facts suggests the great importance to lucerne of its winter-dormancy period. Neither in its seedling year nor in later years should the winter rest of lucerne be disturbed, if the best kind of stand is to be secured.

As already mentioned in the discussion of Hansen's results (see above),

it is necessary to separate the effects of lateness of cutting from those of frequency of cutting. Experiments on frequency of cutting have in some instances led to the taking of cuttings late in the year in order to crowd a number into one season. Amongst observations that have been made on the effects of late cutting of lucerne, those of Grandfield [19] may be quoted. Grandfield's findings confirm the recommendations of Moore and Graber [20]; his data are more specific than any others available, but his paper is difficult to abstract.

Grandfield's lucerne was sown in the autumn of 1928; his experiments began in the summer of 1929, and observations on the thickness of the stands were made until 1932 inclusive. A material loss of plants occurred where the plots were not protected through the winter. Protection of the plots (in reality, of the plants) was obtained by allowing the plants to remain uncut, so that the new growth after cutting was allowed to act as a mulch (as recommended by Thornton and Nicol [1]). The last cuts were made at various times, so that periods of 0 to 120 days elapsed before winter stopped growth. Three varieties of lucerne were tested, and, though these showed different degrees of winter-hardiness, the general conclusions were the same for all. No correlation was found between hardiness and liability to wilt disease. Grandfield recommended that lucerne should be allowed a growing period of 40 days after the last cutting; the length of the growing period before the onset of winter was a factor in maintaining the stands. Grandfield did not specify the location of his plots, but it may be assumed that the experiment was performed in Kansas. Albert [21], who examined more specifically the causes predisposing to winter-killing, concluded that 'the protection afforded to alfalfa plants by even small amounts of late-fall top-growth has a pronounced effect toward preventing winter-killing'. He also found that cutting the top-growth of plants at relatively immature stages retarded root-development.

Janssen [22] made some investigations upon varietal resistance to winter-killing. He gave weights of roots but did not clip the tops. The importance of his paper, from our point of view, lies in his demonstrations of the value of root-reserves and of the connexion between winter-killing and weed-invasion. Illustrations of badly winter-killed stands after late cutting were given by Moore and Graber [20]. Root-habit also plays a part in resistance to winter-killing (which is largely ascribable to the effects of alternate freezing and thawing, Southworth [23], Garver [24]), the branched roots of Grimm lucerne being particularly well adapted to resist heaving. Southworth has given several early references to the question of root-habit. For the effect of soil structure on root-systems of lucerne, see Carlson [25].

Salmon, Swanson, and McCampbell [26] in Kansas, working in 1914 with lucerne sown in 1912, made all their last cuts about the same time, thus eliminating the factor of late cutting studied by Grandfield. They found, in agreement with McKee [6] and Nelson [27], that early cutting reduced root-diameter. It also led to a reduction in the number of plants per plot (McKee) and to an increased invasion by grass. Nelson [27], who worked in 1921–3, inclusive, with lucerne sown in 1920 and left

undisturbed that year, did not publish absolute weights of lucerne roots but correlated weights with root-diameters; he also determined carbohydrate reserves as percentages. His presentation is neither uniformly made nor easy to follow, but it seems clear (if one of his minus figures is correctly interpreted as a gain) that the effect of clipping was to increase the soluble carbohydrate and to depress the amounts of other analysed constituents of the root. A review of the chemistry of reserves in lucerne has been made by Graber *et al.* [12], and by Leukel [28]—presumably the same as the Luekel of Graber *et al.* [12]. He concluded that lucerne cut frequently or late in the season in the succulent growth-stage goes into winter-dormancy low in organic root-reserves, and may suffer severe winter-injury. Albert [21] found that excessive cutting led to winter-killing, weed-invasion, and reduced life of crop, whether grass or lucerne: 'The initiation of new root-growth does not seem to occur to an appreciable extent until the rate of growth of the tops is relatively slow.'

The conclusions of the American workers just mentioned were strikingly anticipated by Graber [29] in a theoretical paper in which he pointed out that lucerne, by virtue of its clear-cut responses to cutting treatments, was a particularly valuable plant for investigations on root-reserves. Graber concluded that excessive or late cutting would lead to:

1. Smaller root reserves.
2. Lessened absorptive capacity.
3. Winter-killing.
4. Increased competition from weeds, due to thinning of the stand.

IV. *The Effects of Cutting Lucerne upon its Ability to resist Drought*

No record has been found of any experiment designed to examine drought-resistance in lucerne, but the foregoing discussion appears applicable to the problem of drought-resistance. Bates [30], who accords classical status to the work of Stapledon [31], wrote: 'It is a fact now generally accepted that the effect of denudation of foliage is to reduce the size and extent of the root-system.' This obviously has a bearing upon the drought-resistance of a normally deep-rooted plant such as lucerne. In fact, the demand which well-grown lucerne makes upon subsoil water is so striking [32, 33, 34, 35] that it has been proposed to employ lucerne to lower the water-table under irrigated land [36].

Woodman, Evans, and Norman have recorded analyses of repeated cuttings made in 1-year-old and 2-year-old lucerne grown in Cambridgeshire. Their 1-year-old lucerne, sown at Howe Hill on light, gravelly soil in June 1932, was first mown in September 1932. The 2-year-old-stand was sown at Willingham on a deeper and heavier soil in June 1931 and cut twice in 1932. It is not recorded in their papers [37, 38] whether the Willingham lucerne was mown in 1931. A 'one-year-old stand', as that term is used by Woodman and his co-workers, is not the same thing as first-year, spring-sown lucerne, that is, lucerne sown about April.

Woodman and co-workers noted [38] that the 1-year-old lucerne at Howe Hill suffered severely during the drought of 1933; and claimed that this showed that light and fairly dry soils must be deep and not

easily dried out if lucerne is to maintain its reputation for enduring droughts. Whilst the shallowness of the soil may have been a factor contributing to the severity with which the lucerne at Howe Hill suffered from the dry weather in 1933, it is probable that the lateness of sowing (June) and the September cutting in the first year materially prejudiced the ability of the plants to withstand a drought in the following year. It is important to stress the effect of cutting the 3-months-old lucerne in 1932 upon the root-development in 1933. Given an adequate root-system, the lucerne plants at Howe Hill would probably have been able to withstand the 1933 drought even in a light, gravelly soil. Woodman *et al.* claimed that the results in 1933 have a special interest, in that they afford an insight into the influence of a prolonged drought on the yield, feeding-value, and general well-being of the crop. At least as far as yield and general well-being of the crop are concerned, this claim is of little value unless the effects of the previous year's treatment (June sowing and September mowing) are adequately considered. Cutting the tops dwarfs the roots, and, in Bates's words [30]: 'It is obvious that a restricted root-range will entail a limited water-supply.'

These considerations suggest that where lucerne is sown on gravelly soils, it should be sown about April if a cutting is desired in the year of sowing. If lucerne is sown in summer on soils liable to dry out, it should not be cut in the year of sowing if drought-resistance and a long duration of stand are desired.

V (*a*). *Effects of Clipping Clovers, Grasses, and Non-Legumes*

Lucerne is not peculiar in its root-response to defoliation. The effect, upon roots, over two seasons, of cutting the tops of grasses has been well studied by Stapledon [31], whose work, however, does not appear to be so well known to American agronomists as it should be. Other workers who may be mentioned here are Arny [39], Paterson [40], Richardson *et al.* [41], Robertson [42], Parker and Sampson [43], and McCarty [44]. Sinclair [45] indeed in 1824 wrote: 'Nothing retards the after-growth of grasses so much as close cropping their first shoots, early in the spring.' His use of the term 'grass' included the clovers. Albert [21] found with two grasses that removal of the autumn growth appreciably lessened the amount of top-growth produced in the following season. Stewart [46] found that sweet clover (*Melilotus*) when closely cut produced little or no second growth. Bates' [30] work on *Trifolium* has already been mentioned. Voelcker showed in an interesting paper [47] that close grazing of clover led to a diminution in the residual manurial value to following wheat. Pierre and Bertram [48] working with the legume, kudzu, found its response to cutting to be closely similar to that of lucerne.

(*b*) *The Early Bite on Grassland*

The investigations here described undoubtedly have a bearing upon a dilemma which is experienced every spring by many farmers and graziers in Great Britain, even when their grassland does not contain lucerne; that is, the problem of the 'early bite'. There is a considerable temptation to turn stock on to the pastures and meadows in the early

spring, especially if stocks of hay and roots are short. Access to young grass is good for the stock, but it is always a question how far the utilization of the 'early bite' is economic. How far does grazing early in the year retard the development of grass and thus affect the ultimate yield from the grassland?

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